FINAL REPORT

Electromagnetic Surveys for 3-D Imaging of Subsurface Contaminants

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Naval Facilities Engineering Service Center

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University of Missouri-Columbia

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ACRONYMS AND ABBREVIATIONS

1,2-DCE	1,2- dichloroethylene
3-D	three-dimensional
A	amperes
AFB	Air Force Base
AWAC	Airborne Warning and Control System
bgs	below ground surface
BRAC	Base Realignment and Closure
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CPT	cone penetrometer testing
CVOC	chlorinated volatile organic compounds
DCA	di-chloroacetic acid
DCE	1,1 dichloroethane
DNAPL	Dense Non-Aqueous Phase Liquid
DOD	Department of Defense
EM	electromagnetic
EOL	Electromagnetic Offset Log
EPA	Environmental Protection Agency
ESOH	Environment Safety and Occupational Health
ESTCP	Environmental Security Technology Certification Program
ESTRG	Environmental Security Technology Requirements Group
FID	flame ionization detector
ft	feet
GC/MS	gas chromatography/mass spectrometry
GP	Geoprobe®- installed microwell
Hz	Hertz
IDL	instrument detection limit
IDW	investigation derived wastes
LNAPL	light non-aqueous phase liquid
mA	milliamps
MCL	maximum contaminant limits
mL	milliliters
mV	millivolts
NA	not applicable
NADEP	Naval Air Depot

NAS	Naval Air Station
NAPL	non-aqueous phase liquid
ND	not detected
NFESC	Naval Facilities Engineering Service Center
O&M	operation and maintenance
ohm-m	ohm-meters
PCE	tetrachloroethylene
ppb	parts per billion
ppm	parts per million
PVC	polyvinyl chloride
QA/QC	Quality Assurance and Quality Control
RCRA	Resource Conservation and Recovery Act
RHOA	resistivity horizontal affect
ROD	Record of Decision
SCAPS	Site Characterization and Analysis Penetrometer System
TCA	1,1,1-Trichloroethane
TCE	Trichloroethylene
TPH	total petroleum hydrocarbon
U of M	University of Missouri, Center for Environmental Technology
UST	underground storage tank
VOA	volatile organic analysis
VOC	volatile organic compound

EXECUTIVE SUMMARY

This report describes a demonstration sponsored and funded by the Department of Defense's (DoD) Environmental Security Technology Certification Program (ESTCP). GEHM Environmental Corporation and the Center for Environmental Technology at the University of Missouri (Columbia) were contracted by the Naval Facilities Engineering Service Center (NFESC) to investigate the use of quasi-static electromagnetic (EM) resistivity surveys to detect dense non-aqueous phase liquid (DNAPL) contamination in the subsurface at two U.S. DoD installations. This EM resistivity survey technique is a surface to borehole geophysical method that generates a three-dimensional (3-D) image of subsurface features based on their contrasting resistive properties.

The two sites selected were the former Naval Air Station Alameda, renamed Alameda Point, and Tinker Air Force Base. They were selected for this pilot study on the basis of having a previously well-documented DNAPL problem, coupled with the fact that they reside in two distinctly different types of geologic settings. These sites also have typical limitations with respect to drilling restrictions and with respect to the high degree of uncertainty in knowing where free-phase DNAPL currently occurs in the subsurface. Alameda Point's subsurface consists of saturated unconsolidated clastic sediments, while Tinker AFB consists of interbedded sands and shales.

The primary objective of this investigation was to verify that the EM technique could consistently, rapidly and accurately perform high resolution site characterization and DNAPL source delineation. By having a more thorough understanding of the subsurface conditions, monitoring wells can be located and screened at the most effective interval for evaluating DNAPL presence. Recovery wells can be located and screened for optimum free-product removal. Given significant improvements in the performance of these wells, lended by successfully applying this method, substantially fewer wells and sample analyses would be required for a given site, and greater quantities of free-phase DNAPL could be removed more quickly and economically.

The project goal involved successfully predicting the location and extent of subsurface anomalies of suspected DNAPL contamination with the EM technique. However, because all geophysically based subsurface characterizations carry uncertainty, the 3-D EM resistivity method must be accompanied with drilling and sampling to ground-truth the occurrence of DNAPL. As a result, after the geophysical predictions were made, validation drilling and sampling was conducted to verify the presence of DNAPL, thus indicating the accuracy of 3-D EM characterization.

The EM technique images highly resistive fluids and materials, and requires chemical analysis of physical samples to verify subsurface contamination. The verification process is accomplished after acquiring, processing and analyzing the EM resistivity data and generating 3-D computer models of suspected areas of hydrocarbon contamination. A cone-penetrometer truck or drilling rig then samples the subsurface soil to confirm that high concentrations of DNAPL are present in the subsurface. The borehole results are thus used to validate the EM geophysical model. Although one objective of any geophysical survey is to provide the type of subsurface information that is derived from drilling holes, some variation between these methods is expected and they seldom agree completely.

A number of data anomalies were selected as targets for evaluation by conventional drilling and sampling techniques. Groundwater samples were collected and analyzed for the presence of volatile organic compounds (VOCs). DNAPL was considered to be present in the groundwater at a site if the

solubility of a groundwater sample met or exceeded 10 percent of the solubility limit for any DNAPL constituent thought to be present.

The results from the two study sites indicate that EM survey techniques do not adequately predict where significant subsurface DNAPL is located. Results from Tinker AFB indicated that only groundwater results matched EM predictions. At NAS Alameda, an alarming number of "false-negative" findings were discovered. That is, EOL imaging reported little to no concentrations of DNAPL in specific areas. However, later subsurface investigations using laser-induced fluorescence and videoing revealed significant quantities of mixed NAPLs in these same studied areas. A possible source of error that may have led to these discrepancies was a result of the level of subsurface DNAPL being too diffuse to significantly alter the resistivity of the sediments. Due to the inconsistent results of this project, this technology has not demonstrated the required performance capabilities enabling it to be compared to the more conventional methods currently used to characterize DNAPL sites.

This study clearly shows that EM technology will not successfully detect low concentrations of DNAPL in soil and sediments. Based on the results of the demonstration, it appears doubtful, given the types of conditions that DNAPL are thought to typically accumulate and reside in the subsurface (e.g., in small, scattered pools and ganglia), whether the EM resistivity method can distinguish between aqueous media and the DNAPLs and/or their dissolved-phase constituents.

Section 1.0 INTRODUCTION

This report describes a demonstration sponsored and funded by the DoD's Environmental Security Technology Certification Program (ESTCP). The following demonstration investigated the use of quasi-static EM resistivity surveys to detect and generate 3-D images of subsurface DNAPL contamination. This EM resistivity survey technique is a surface to borehole geophysical method that generates a 3-D image of DNAPL-contaminated subsurface zones based on their high resistive properties as contrasted with non-contaminated subsurface soil, rock and groundwater.

GEHM Environmental Corporation and the Center for Environmental Technology at the University of Missouri contracted with the Naval Facilities Engineering Service Center (NFESC) under Contract Number N47408-97-C0213 to conduct the 3-D EM survey application at two DoD installations known to have subsurface DNAPL contamination. If this technique is proven to be a viable method to consistently, rapidly and accurately perform high resolution site characterization and DNAPL source delineation, it may significantly assist in the direct remediation of source zone contamination. The objective of this study was to test the ability of EM resistivity surveys to find subsurface DNAPL.

1.1 Background Information

The challenges and problems of site characterization and remediation are further complicated by the presence of DNAPLs. The complex nature of DNAPL transport and fate often inhibits its detection by direct methods, leading to incomplete site assessments and sub-optimal remedial design. High specific gravity, low viscosity, and very low solubility in water characterize these separate-phase hydrocarbon liquids which sink to the bottom of aquifers. The movement of free-phase DNAPL is strongly dependent upon the subsurface stratigraphy, particularly the distribution of zones of high permeability, such as faults, bedding planes, and sand channels, which act as preferential pathways for DNAPL migration.

Usually, most of the contaminant mass at a DNAPL site is centered in the source zone. In addition, DNAPLs undergo only limited degradation in the subsurface, and persist for long periods while slowly releasing soluble organic constituents to groundwater through dissolution. As a result, the trapped DNAPL that remains in the soil/aquifer matrix acts as a continuing source of dissolved contaminants to the groundwater. Because of this, it is necessary that the contaminant mass be removed from the source zone in order to restore the aquifer to drinking water standards. Unfortunately, conventional methods such as drilling and sampling do not accurately characterize the heterogeneities through which DNAPL may migrate; nor have conventional aquifer remediation approaches, such as pump-and-treat, removed more than a small fraction of trapped residual DNAPL (Pankow and Cherry, 1996).

1.2 Official DoD Requirement Statements

Table 1 provides relevant Environment Safety and Occupational Health (ESOH) needs of the DoD as specified by the Environmental Security Technology Requirements Group (ESTRG). These needs were identified by searching the FY'97 DoD Environmental Technology Requirements Strategy (DETRS) website, available at http://xre22.brooks.af.mil/estrg/estrgPwdPage.htm.

DETRS was prepared in order to document the broad technology goals and service prioritized user requirements. This strategy does the following:

- Serves to focus the programs of the DoD environmental RDT&E community by providing an integrated view of the DoD user needs.
- Serves as a vehicle for coordinating DoD technology development needs with other Federal agencies in the national environmental program.
- Serves to identify to the private and non-government organization sectors the priority environmental technology requirements of DoD.

More specifically, this effort supports the following Navy Tri-service Environmental Quality user requirement:

1.III.2.a Remote Sensing for Site Characterization and Monitoring

Table 1. Relevant ESOH Needs of DoD as Specified by ESTRG

Organization	Applicability	Identification Number	Description
		Army Needs	
Army-wide	Direct	A(1.1.k)	Develop Innovative Alternative (and Non-Invasive) Techniques for Subsurface Characterization (96-97)
		A(4.2.a)	Land Capability/Characterization
		Navy Needs	
Navy-wide	Direct	(1.III.1.k)	Improved field analytical sensors, toxicity assays, methods, and protocols to supplement traditional sampling and laboratory analysis
		(2.II.2.b)	Improved field analytical sensors, toxicity assays, methods, and protocols to supplement traditional sampling and laboratory analysis
	Related	(1.I.1.g)	Improved remediation of groundwater contaminated with chlorinated hydrocarbons and other organics
		Air Force Needs	
Air Force Flight Test Center	Related	1611	Treatment of Chlorinated Hydrocarbons
Arnold Engineering Development Center	Direct	701	In Situ Treatment for Dense, Nonaqueous-Phase Liquids
Odgen Air Logistics Center	Direct	246	New Technology to Identify and Quantify Chlorinated Organic Compound Concentrations for Installation Restoration Program Site Investigation/Remediation Monitoring
	Related	255	Improve Understanding of DNAPL Groundwater Transport to Accurately Predict Fate of Contaminants
		271	Fate and Transport of Chlorinated Solvent Plumes in Vadose Zone
		281	Hazardous Waste Treatment Technologies for Installation Restoration Program Site Remediation of the Plumes of Chlorinated Organic Compounds
Oklahoma City Air Logistics Center	Direct	130	Effective DNAPL Characterization, Monitoring, and Detection Technology
Sacramento Air Logistics Center	Direct	570	Improve Understanding of DNAPL Groundwater Transport to Accurately Predict Fate of Contaminants
	Related	557	Fate and Transport of Chlorinated Solvent Plumes in Vadose Zone
San Antonio Air Logistics Center	Related	641	Fate and Transport of Chlorinated Solvent Plumes in Vadose Zone

1.3 Objectives of the Demonstration

The objective of this project was to assess the effectiveness of 3-D EM resistivity surveying as a method for performing site characterization and subsurface DNAPL source delineation. The 3-D EM resistivity method has been successfully used in the past to image subsurface light, non-aqueous phase liquid (LNAPL) plumes (Pritchard, 1995; Maxwell, 1995; GEHM, 1996). This project's effort involved demonstrating the ability of this EM method to generate 3-D images of subsurface DNAPL contamination. Collecting subsurface physical samples within the surveyed region validated the accuracy of the survey results and predictions. Soil and groundwater samples were collected using direct-push and rotary drilling methods.

EM survey-based DNAPL source delineation was deemed to be successful if 90% of the predictions for DNAPL contamination could be verified, based on physical and chemical analyses of samples taken from within the surveyed regions.

The following two sites were selected for this project to demonstrate 3-D EM resistivity surveys under different conditions:

- Alameda Point, California – Building 5 (plating shop)
- Tinker Air Force Base (AFB), Oklahoma – Building 3001 (degreasing operation).

The two sites were selected because they each have a well-documented DNAPL problem and because their geologic settings differed significantly. Alameda Point's subsurface is characterized as a saturated sediment, while Tinker AFB's is interbedded sands and shales.

1.4 Regulatory Issues

Electromagnetic resistivity surveys are relatively non-invasive; however, they do require that at least two instrumentation wells are located and, if necessary, installed within a few hundred feet of the region of interest. In addition, subsurface samples must be taken, using either conventional drilling and sampling techniques or direct push methods. As a result, standard drilling permits and underground utility clearances were required prior to commencing this stage of work. The prevention of cross contamination through an upper confining layer situated above an uncontaminated aquifer is a primary concern at any site. Steps were taken to mitigate this regulatory concern by destroying and grouting all wells and borings immediately after being used.

The contractors also disposed of investigation-derived wastes (IDW) that were generated during this effort in accordance with Resource Conservation and Recovery Act (RCRA) guidelines. IDW consisted of the wash-down water used to decontaminate the Geoprobe and SCAPS probes and samplers after each use, as well as all borehole and well drill cuttings. These wastes were contained in 55-gallon drums per regulatory requirements. An additional permit was required to temporarily accumulate the IDW at the site.

A final regulatory issue involved the transmission of electromagnetic radiation form the equipment. The magnitude of the electromagnetic field generated by the signal transmitter was less than an EM field generated by the 15-amp (A) power lines in a 10 x 10-foot room, when standing 4 feet from the transmitter. Thus, the magnitude of EM radiation at the site was relatively small. Regulatory and safety issues were avoided by maintaining a 4-foot safety distance from the energized transmitter. Due to these considerations, a special permit to operate the EM technology was not required.

1.5 Previous Testing of the Technology

This 3-D EM resistivity technology has been used successfully in the past to image LNAPL contamination based on its high resistivity characteristics (Pritchard, 1995; Maxwell, 1995; GEHM, 1996). Although detection limits may vary between sites, contaminant levels of 100 parts per million (ppm) LNAPL have typically shown to be sufficient for generating a high resistivity anomaly that can be imaged in the survey model (GEHM, 1996). Both free-phase LNAPL and DNAPL have the same resistivity values (approximately 1×10^6 ohm-meters), which are higher than typical bulk, groundwater-saturated, geologic media. The ability for this technology to detect subsurface DNAPL contamination has not previously been tested or demonstrated.

Section 2.0 TECHNOLOGY DESCRIPTION

2.1 Description

The quasi-static EM resistivity survey is a surface source to an in-hole receiver geophysical technique used to generate 3-D images of subsurface features by measuring variations in resistivity within a medium. For example, all free hydrocarbons are highly resistive while subsurface waters are much lower in resistivity. By measuring resistivity contrasts within the subsurface, one can predict the presence of hydrocarbon plumes. The resistivities are displayed and visualized in three dimensions to give interpreters a "CAT Scan" type of image of the subsurface.

This technology has been used successfully in exploration of natural resources (i.e., mining, oil and gas, subsurface freshwater) since the 1960s. Recent advances in instrumentation have enabled this technique to be used in relatively shallow applications. Presently, Electromagnetic Offset Log (EOL) models cannot be used to document soil and water contamination, *as a stand-alone process*. The EOL process merely images highly resistive and low resistive features related to fluids and materials. The results of the EOL project must undergo a comparative analysis with existing truth data (i.e., soil chemical data) and with post-EOL process data. However, the amount of post-EOL truth data that is required will always be much less than that which would be required if EOL was not performed. The objective of an EOL site survey is to provide on-site program managers with a quicker, and much less expensive depiction of the vertical and horizontal extent of a contaminated plume.

EM resistivity surveys have been used successfully to accurately portray subsurface plumes generated from LNAPL (i.e., fuel) contamination (Pritchard, 1995). The presence of fuel contamination in the subsurface produces high resistivity anomalies due to the presence of high resistive hydrocarbon molecules. The 3-D image in Figure 1 shows high resistive regions detected beneath a fuel pipeline. These regions are likely to contain hydrocarbon contamination.

This project hoped to establish that the same EM resistivity technique and method that successfully delineated LNAPLs could also accurately delineate a DNAPL plume. No provisions or modifications to the basic EM technology were employed for the specific detection of DNAPLs. Adjustments were made only in raw data interpretation in order to account for site-specific geological characteristics that impacted resistivity patterns.

A minimum resistivity contrast of 1.5 is required to distinguish between different subsurface features. Non-dissolved DNAPLs and LNAPLs have resistivity properties exceeding 1 x 10^6 ohm-meters. The following table lists resistivity values, in ohm-meters, for various saturated lithological materials. Vadose zone (unsaturated) soils have resistivities that are 10-50 times the resistivity of saturated soil.

Saturated Soil	Ohm-Meter	Saturated Rock	Ohm-Meter
clay/mud	2-5	Shale	1-10
silt	5-20	Sandstone	10-50
sand	10-50	Volcanic rock	100-500
gravel	20-50	Metamorphic rock	300-1,000
		limestone	50-10,000

The process of conducting a 3-D EM resistivity survey consists of the following steps:

- Conduct a complete review of all available geologic/hydrogeologic information and site specific sources of DNAPL contamination, as well as sources of cultural and electrical noise.
- Install two or more instrumentation wells to allow redundant signal paths and to ensure good data quality. Installation consists of constructing wells with 2-inch polyvinyl chloride (PVC) casing. Due to physical limitation, maximum well depth cannot exceed 300 feet.
- Place an EM receiver sensor in the instrumentation well.
- Induce a magnetic field into the earth at points located around the well.
- Record the EM signal at the sensor. These data can produce a cross-sectional view of the subsurface between the sensor and the point of induction. For each point, the sensor is positioned at 0.1 foot increments from the bottom of the well up to ground level. As the point and sensor are moved, a 3-D matrix of data is generated of the EM intensity.
- Process the data and generate a 3-D representation of relative resistance.
- Locate the subsurface DNAPL contamination by identifying localized regions of increased relative resistivity (a resistive anomaly).
- Identify stratigraphic features by differentiating zones of smaller systematic resistivity differences.
- Collect three physical samples of media (low, medium, and high contamination predictions) for ground truth. Verification samples are collected by the technology demonstrators after each prediction.

The primary electromagnetic field consists of a large, long wavelength signal (1,400 amp-meter^2 EM moment at the surface, 263 hertz (Hz)). The primary signal response is strongly influenced by regions of very high resistivity. Superimposed on this primary source signal response are the much smaller amplitude signal responses from the secondary subsurface currents, which are generated at the boundaries and within the bodies of resistivity change. The primary and secondary fields are converted to apparent resistivity (from voltage to ohm-meters) to identify the presence of highly resistive anomalies (i.e., contamination) and the physical properties in the earth, respectively.

The transmitter coil and receiver are tuned to a narrow bandwidth of 263 Hz. This tuning procedure, along with optimizing receiver well locations based on low noise levels, is designed to filter out electrical noise. This allows the EM resistivity surveys to be conducted in and around man-made structures and other sources of electrical noise.

Other potential noise generators such as buried man-made objects, the locations of which are often unknown, produce unwanted secondary currents and an undefined attenuation of the amplitude in the expected primary field strength; an effect known as "amplitude static". The shape of the signal's amplitude from a metal object often helps an analyst to identify and eliminate its effect. Without careful consideration, the secondary current depths of such metal features become depths of no-record, and these volumes are omitted from the processed data. However, the zones below often provide valid data, and are included in the survey results.

Naturally occurring subsurface ferro-magnetic materials do not impact measurable resistivity changes, and do not affect this technology. Also, since the instrumentation is located either down-hole

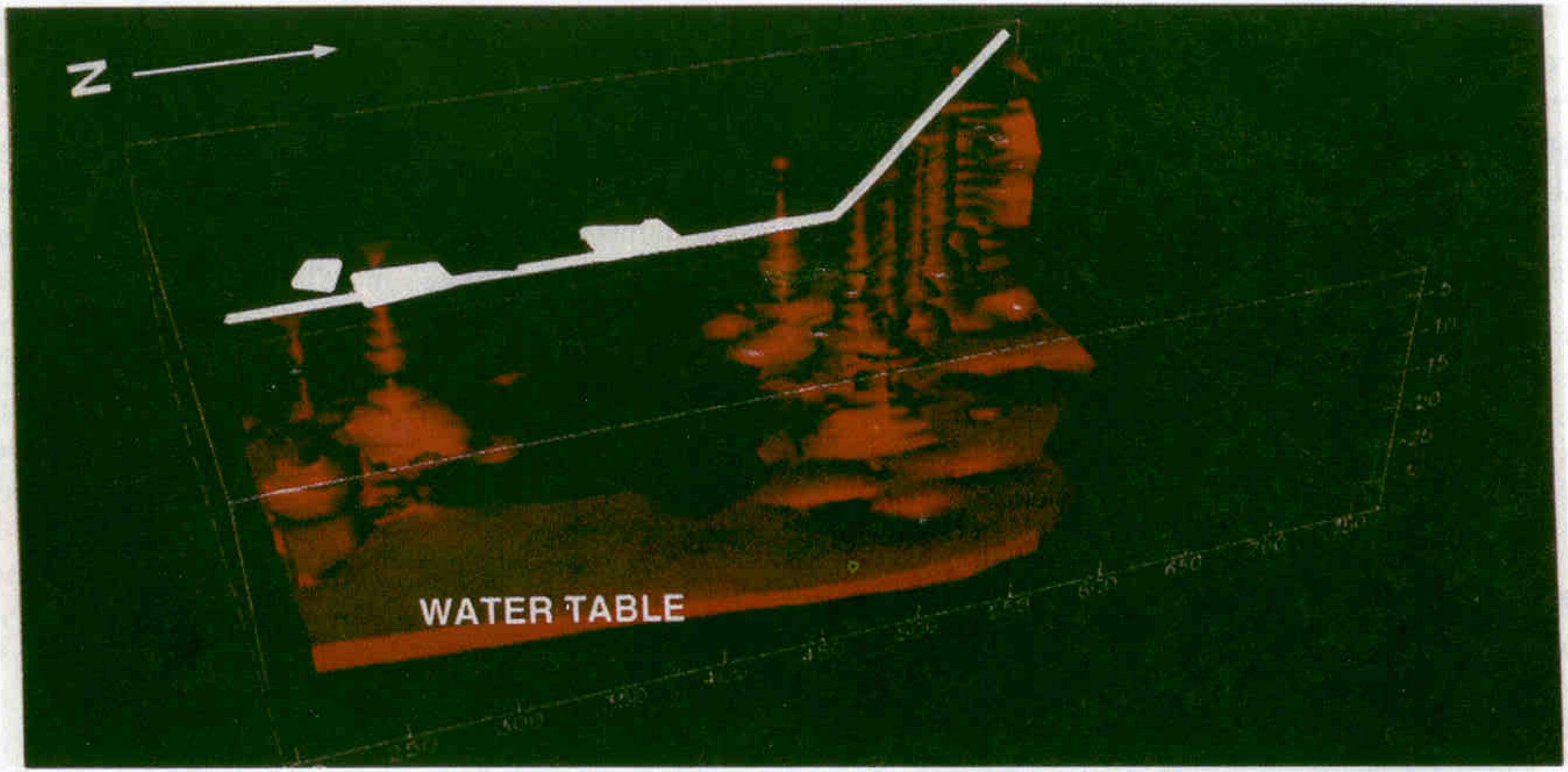


Figure 1. West Texas Pipeline Area High Resistivity Anomalies in the Vadose Zone and at the Water Table

or in a sheltered enclosure, weather conditions do not affect the data collection process. Fieldwork is stopped during electrical storms.

The resolution of the survey data can vary depending on the transmitter location grid spacing. For surface grid spacings of 20 feet, the survey results are typically accurate to within 2 feet vertically and 10 feet laterally. Although its location may not be finely resolved, a film of free-product contamination can be detected with this EM resistivity technique (Pritchard, 1995).

Each survey and analysis is based on tens of thousands of sampled data points. The processed data can be presented either in three dimensions or as depth-specific slice and cross-section images. Contours of relative resistivity in either of these formats can be developed and used to track the resistivity patterns of the soils or other near-surface materials. Higher contaminant concentrations will be represented by higher resistivity values. This relationship is not always linear, however, due to unrelated changes in geology within a contaminated area that may also impact resistivity readings.

2.2 Advantages and Limitations of the Technology

2.2.1 Advantages. The data collection process for EM resistivity surveys is only slightly invasive. Hence, site characterizations can be accomplished at high traffic and inaccessible areas with little or no impact to the site activities.

This EM resistivity method may provide detailed 3-D images of subsurface hydrocarbon contamination and geologic features. The accurate imaging of subsurface site contamination enables focused subsurface source zone remediation. The direct treatment of the contaminant source zone is significantly more effective than the current methods of treating or containing the dissolved constituents generated by the source zone.

Accurate subsurface images provide a more thorough understanding of the subsurface environment, so that monitoring wells can be located and screened at the most effective interval for evaluating DNAPL presence. In turn, recovery wells can be located and screened for optimum product removal. With such significant improvements in recovery well installation and performance, substantially fewer wells are required to remove the DNAPL at a site.

2.2.2 Limitations. The 3-D EM resistivity method is not a stand-alone means of effective site characterization. This technique is interpretative, as it images any highly resistive fluids and materials in the subsurface. It requires confirmatory (validation) sampling and chemical analyses to verify that subsurface contamination is present. The validation process is accomplished after acquiring, processing and analyzing the EM resistivity data and generating 3-D computer models and images of suspected areas having contamination. A drilling or CPT rig advances soil borings in the surveyed areas believed to have high concentrations of DNAPL in the subsurface. The bore hole results are used as truth data for comparative analysis of the EM geophysical model. Although the objective of any geophysical survey is to provide information similar to that from drill holes, some variation is expected and they seldom agree completely.

There has also been some concern regarding the technology's capability to detect DNAPL configurations, e.g. residual globules, ganglia, and small pools, that are potentially out-of-range of the instrument's spatial resolution. This is believed to be a significant source of error when delineating areas with low levels of DNAPL saturation. It is presumed that though LNAPLs and DNAPLs are similar in resistivity, their difference in density can significantly impact mass distribution in the subsurface.

LNAPL tends to collect in a narrow vertical range in the capillary fringe at or just above the water table forming a layer of low electrical conductivity just above the more conductive water and saturated sediments. DNAPLs can be found in regions of relatively low mass per volume. Here, mass is concentrated within a small volume of media. This may contribute to DNAPLs ability or inability to be detected by an EM survey.

In addition, the survey area is limited to a radius of approximately 300 feet around each instrumentation well, so that a survey encompasses a circular area that is about 1.6 acres in size. Hence, the "general" location of a suspected surface source is needed to focus the EM resistivity survey. The depths imaged by this EM resistivity survey are constrained to that of the instrumentation well, which can reach a maximum depth of approximately 300 feet. Hence, the maximum depth of interest needs to be identified before starting the survey, or known to be no more than 300 ft. bgs.

There are certain types of settings where data collection is not possible. For example, an EM resistivity transmitter coil is not effective when situated too close to a large metal object (e.g., a dumpster), or when it is located adjacent to railroad tracks. In these situations, the transmitter coil must be relocated to a more effective position to enable quality data collection.

The companies that provide EM resistivity surveys are very limited in number. The personnel that design the survey and collect resistivity data in the field must have a strong understanding of the technology to ensure that high quality data is obtained. Personnel interpreting survey results must be very experienced and must understand how certain resistivity anomalies relate to site-specific geologic features.

2.3 Factors Influencing Cost and Performance

3-D EM survey costs are dependent on a number of factors, including:

1) the size of the source area
2) the size and depth of the area of concern
3) the resolution required to accurately image the target
4) the type of electromagnetic source (energy input) required to image the target
5) the surface conditions at the site (geologic and cultural)
6) the degree of access allowed in and around the site
7) the amount and availability of pre-existing site information.

Processing costs also impact the total costs of a survey. Generally, processing costs increase as the required resolution and total survey area increase.

Section 3.0 SITE/FACILITY DESCRIPTION

3.1 Background

Two sites were selected for this project in order to demonstrate 3-D EM resistivity surveys in different geologic conditions. The two sites were chosen because they each have a well-documented DNAPL problem and reside in different types of geologic settings. The sites chosen for this demonstration and a general description of their geologic settings are:

- Alameda Point, California – saturated, unconsolidated, clastic sediments
- Tinker AFB, Oklahoma – interbedded, partially lithified sandstone and shale.

Information from previous site investigations (Alameda, CA- Naval Complex; Integrated Environmental Team of Tinker AFB, 1997) was used to design each EM resistivity survey. These site investigation data sets were considered to be typical for most DNAPL-contaminated sites. These data were used to better target the areas likely to have highest DNAPL levels.

Listed below are the highest DNAPL contaminant concentrations in samples collected at the two sites by on-site Remedial Investigation contractors:

- Alameda Point – 1,1,1-Trichloroethane (TCA): 790 parts per million (ppm)
- Tinker AFB – Trichloroethylene (TCE): 250 ppm.

Based on overall site characterization and these specific analytical results, the two sites appeared to be appropriate candidates for the EM survey to detect DNAPL.

The EM resistivity survey site at Alameda Point was located in and around Building 5, a former depot maintenance facility with underground tanks and sewers that were used to contain industrial solvents and wastewaters. Although there was a significant amount of utilities and cultural features at this site, they did not adversely affect the survey data.

The EM resistivity survey site at Tinker AFB was located in and around Building 3001, part of an industrial complex where industrial solvents and wastewaters were contained in unlined subsurface pits and trenches. Despite the presence of buried utilities and various surface impediments, EM survey data were still successfully collected.

3.2 Site Histories

3.2.1 Alameda Point. Alameda Point is located on Alameda Island, in Alameda County, California. The island is located along the eastern side of San Francisco Bay as shown in Figure 2. NAS Alameda occupies 2,634 acres, partially on land and partially submerged, and is approximately 2 miles long and 1 mile wide. Land use in the area includes shipyards, maintenance supply centers, residences, retail businesses, schools, and a state beach. The U.S. Army acquired the area now occupied by Alameda Point in 1930, and construction at this installation began the following year. In 1936 the base was transferred to the U. S. Navy, and in 1941 more land was annexed to the air station. The primary mission of the former NAS Alameda was to maintain and operate maintenance facilities and provide services and material support to naval aviation activities and

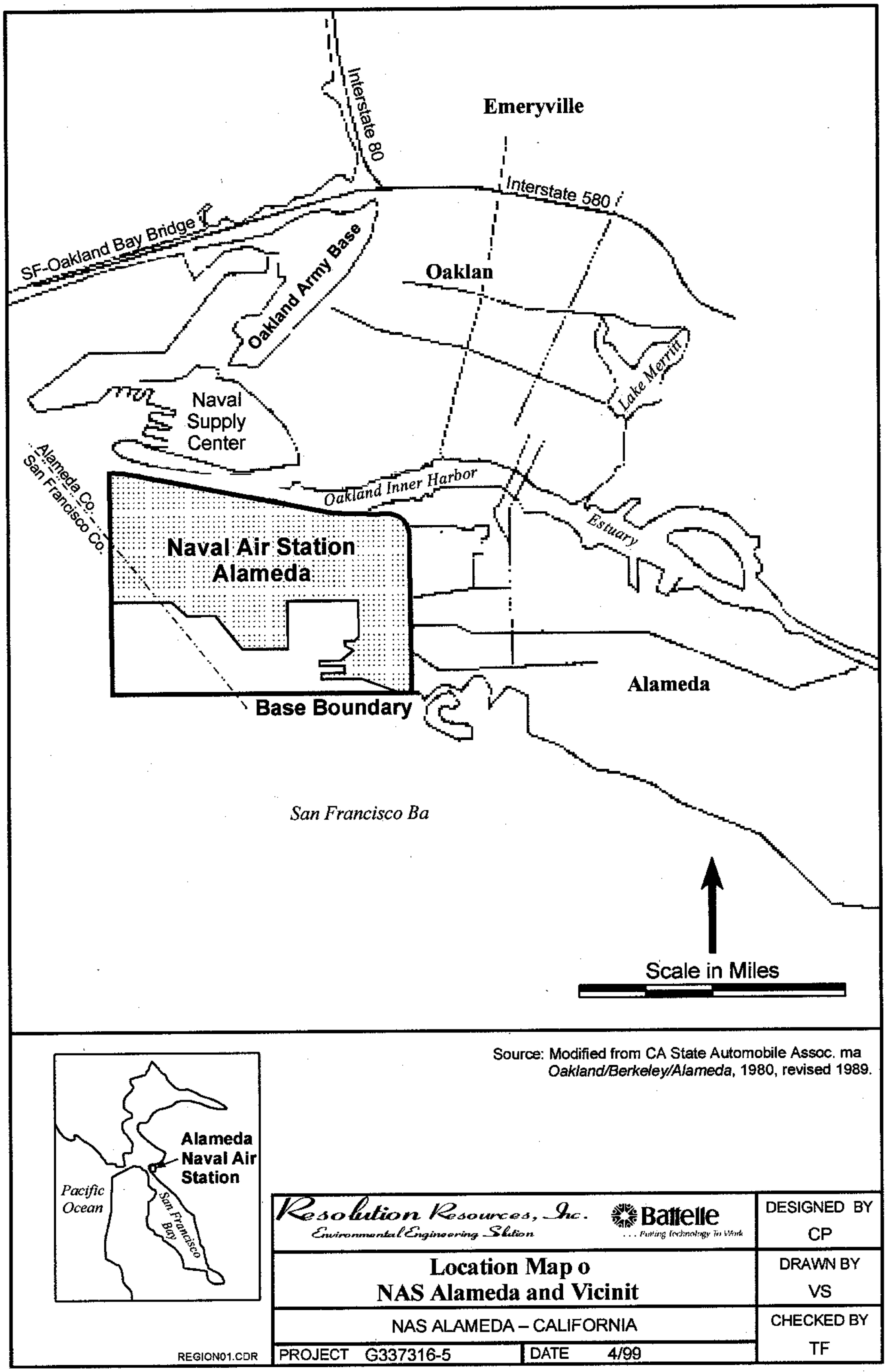


Figure 2. Location Map of Alameda Point and Vicinity

operating forces. The 1993 Base Realignment and Closure (BRAC) commission listed NAS Alameda for closure. In April 1997 the base was closed, turned over to the public, and renamed Alameda Point. BRAC cleanup is now underway, with cleanup to be completed in fiscal year 2007. The Naval Facilities Engineering Command, Western Division, is overseeing the cleanup activities.

The Installation Restoration Program has identified 23 potentially contaminated sites for investigation and cleanup. Site 5 (Building 5 area) was chosen to host the EM subsurface DNAPL imaging demonstration. Figure 3 shows the location of Site 5 within Alameda Point. This site is located in the center of the base, and covers 18.5 acres. It has been in operation since 1942, but has recently been vacated. Shops in the building were used for cleaning, reworking, manufacturing metal parts, tool maintenance, and for plating and painting operations.

The plating shop inside Building 5 has been identified as an area of concern, due to the high concentrations of VOCs in groundwater samples. Processes in the shop included degreasing, caustic and acid etching, metal stripping and cleaning, and chrome, nickel, silver, cadmium, and copper plating. A groundwater sample collected in 1992 from a boring located inside Building 5 at the plating shop showed concentrations of 790 ppm of TCA, indicating that the site was contaminated with significant levels of DNAPL (PRC Environmental Management, Inc., 1994).

Another area of interest is to the east, near the flagpole, where an underground solvent storage tank is located. TCA was detected in soil samples in this area, located on the east side of Building 5. The depths of contaminated soils span from 3 to 14 ft bgs, with concentrations ranging from 0.008 to 39 ppm (PRC Environmental Management, Inc., 1996). Also found in the soil were 1,1 dichloroethane (DCE), chloroethane, tetrachloroethylene (PCE), and vinyl chloride, all at relatively low levels. TCE was also encountered on the east side of the site in concentrations from 0.053 to 2.2 ppm. Water samples from 11 wells screened in the first water-bearing zone, mostly around the perimeter of Building 5, show relatively low levels (below 0.5 ppm) of VOCs, with the exception of a well located on the east side of the building. TCA, DCE, 1,2- dichloroethylene (1,2 DCE), chloroethane, and TCE were present in this well for a total VOC concentration of nearly 60 ppm (Naval Facilities Engineering Command, Western Division, 1995).

3.2.2 Tinker AFB. Tinker AFB is located in central Oklahoma, in the southeast portion of the Oklahoma City metropolitan area, in Oklahoma County (see Figure 4). The Base is bounded by Sooner Road to the west, Douglas Boulevard to the east, Interstate 40 to the north, and Southeast 74th Street to the south. Building 3001 is located in the northeast portion of the Base, east of the north-south runway. Figure 5 shows the layout of Tinker AFB, and the location of Building 3001, in the northeast sector.

The Base encompasses 4,541 acres and contains approximately 500 buildings. Tinker AFB, is a worldwide repair depot. Tinker's mission is to manage and maintain the following aircraft: B-1B, B-2, B-52, E-3, and the multipurpose 135 series. Also managed at the Base are the SRAM, SRAMII, ALCM, and GLCM missile systems, as well as the United States Air Force Harpoon Missile. The Base houses the Air Logistics Center and two Air Combat Command units. Tinker is also the main operating Base for aircraft equipped with the Airborne Warning and Control System (AWACS).

The sources contributing to groundwater contamination beneath and adjacent to Building 3001 include the former solvent pits, industrial waste lines, improper tie-ins between storm sewers and wastewater lines, the North Tank Area, and Southwest Tanks. The former solvent pits within the northern end of Building 3001 are thought to be the main source of TCE contamination. At Pit E-105, which is shown in Figure 6, high concentrations of TCE were detected in the soils beneath and adjacent to the pit. The

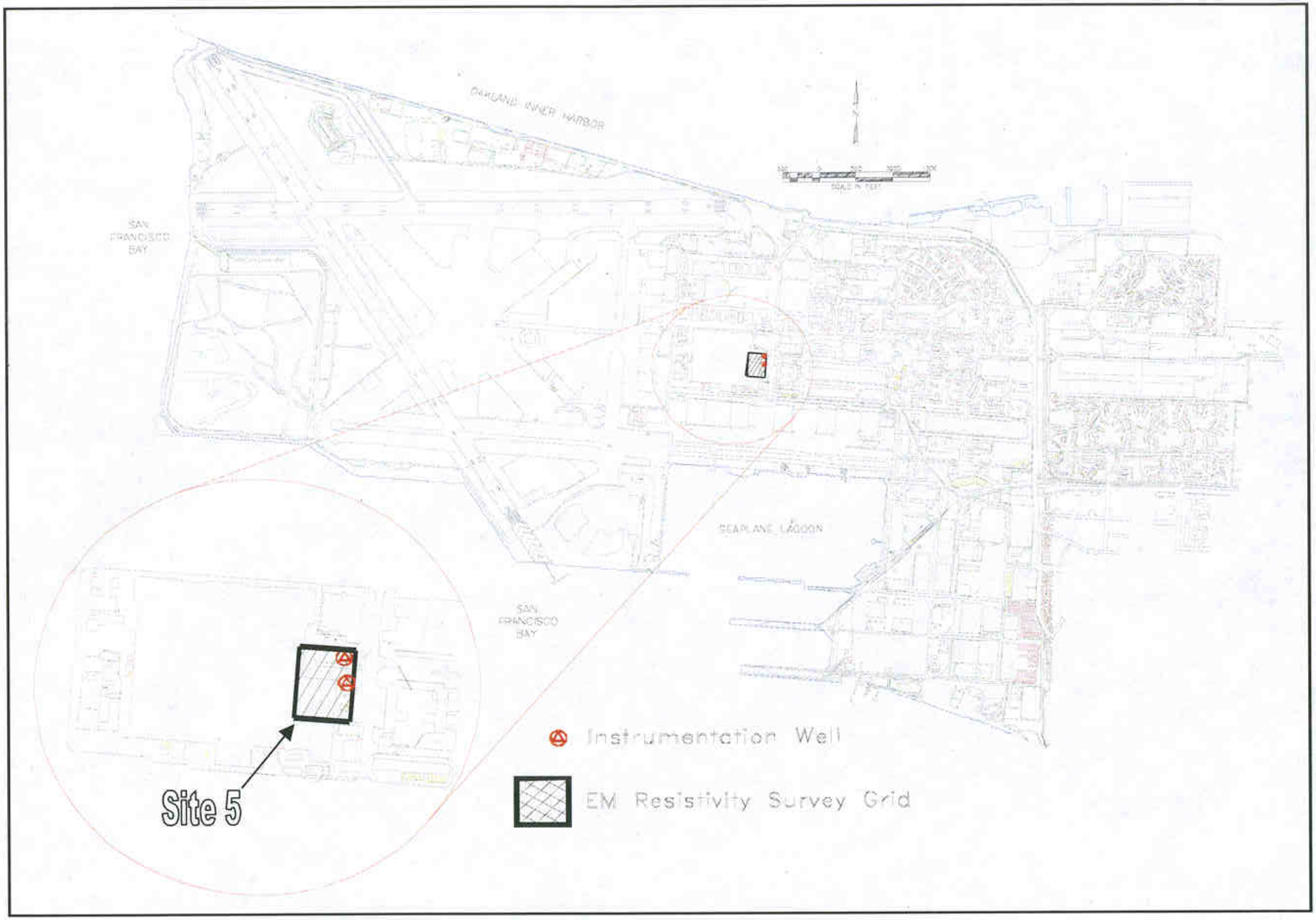


Figure 3. Alameda Point – Site 5

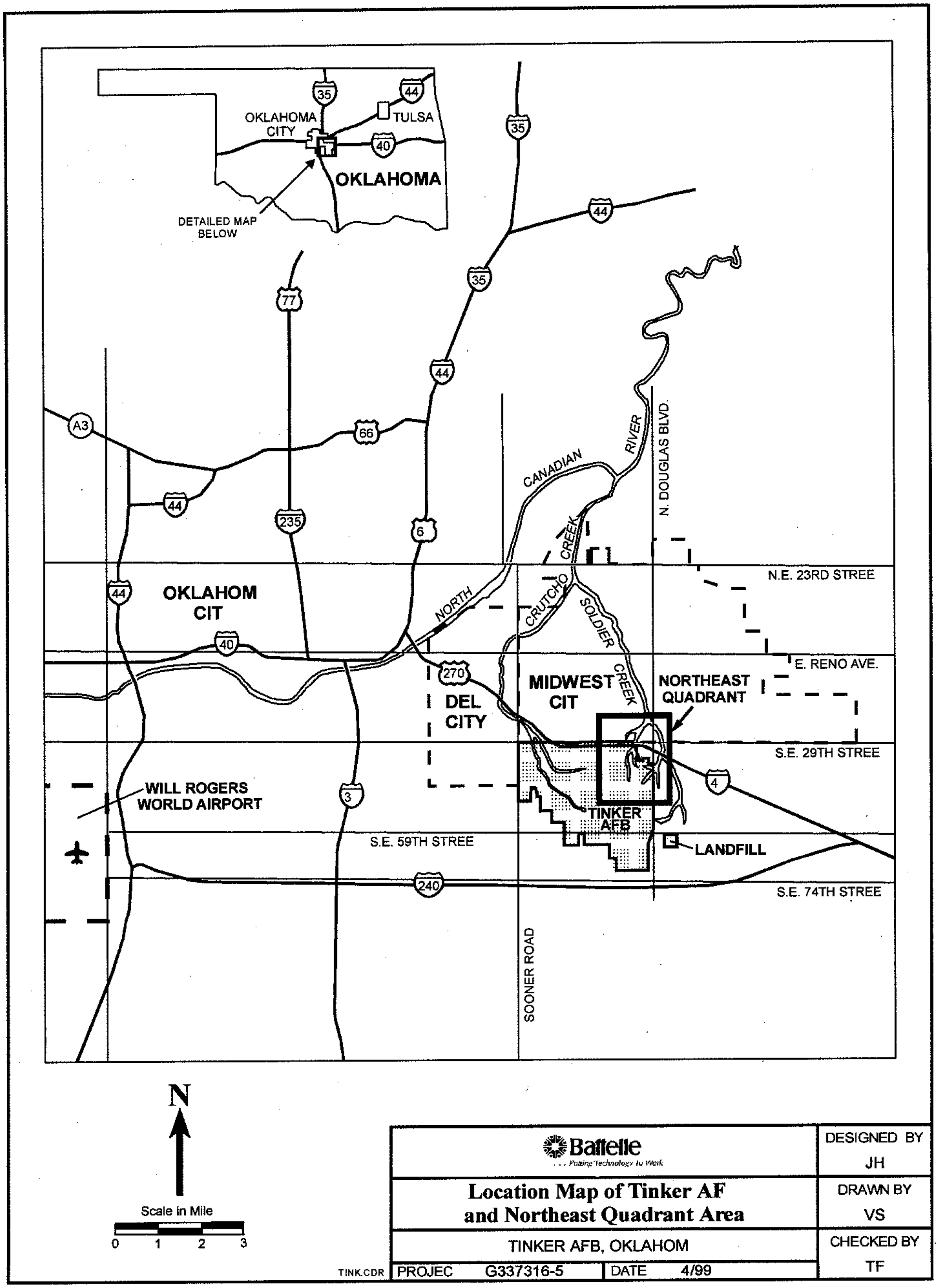


Figure 4. Location Map of Tinker AFB and Northeast Quadrant Area

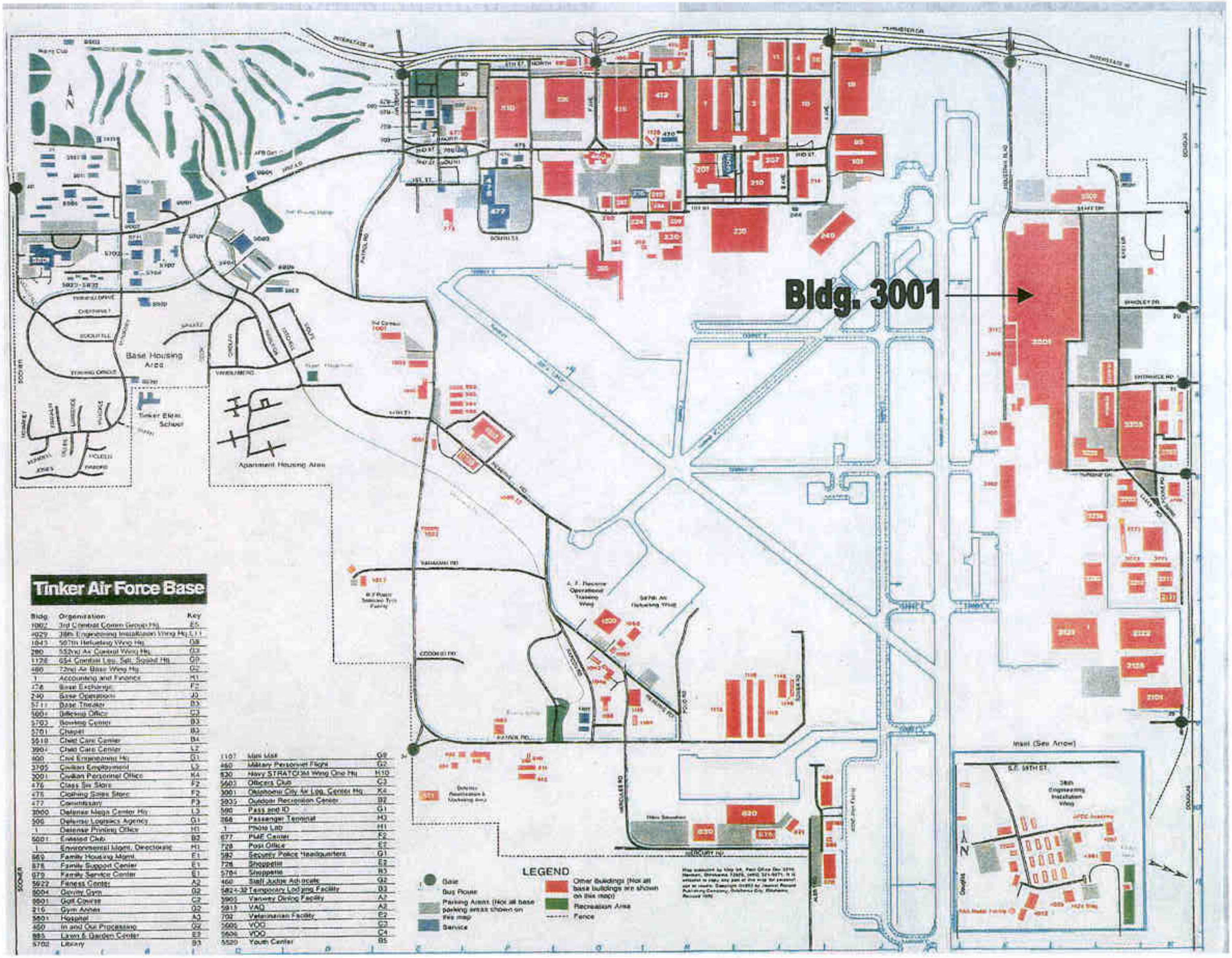


Figure 5. Location of Tinker AFB and Building 3001

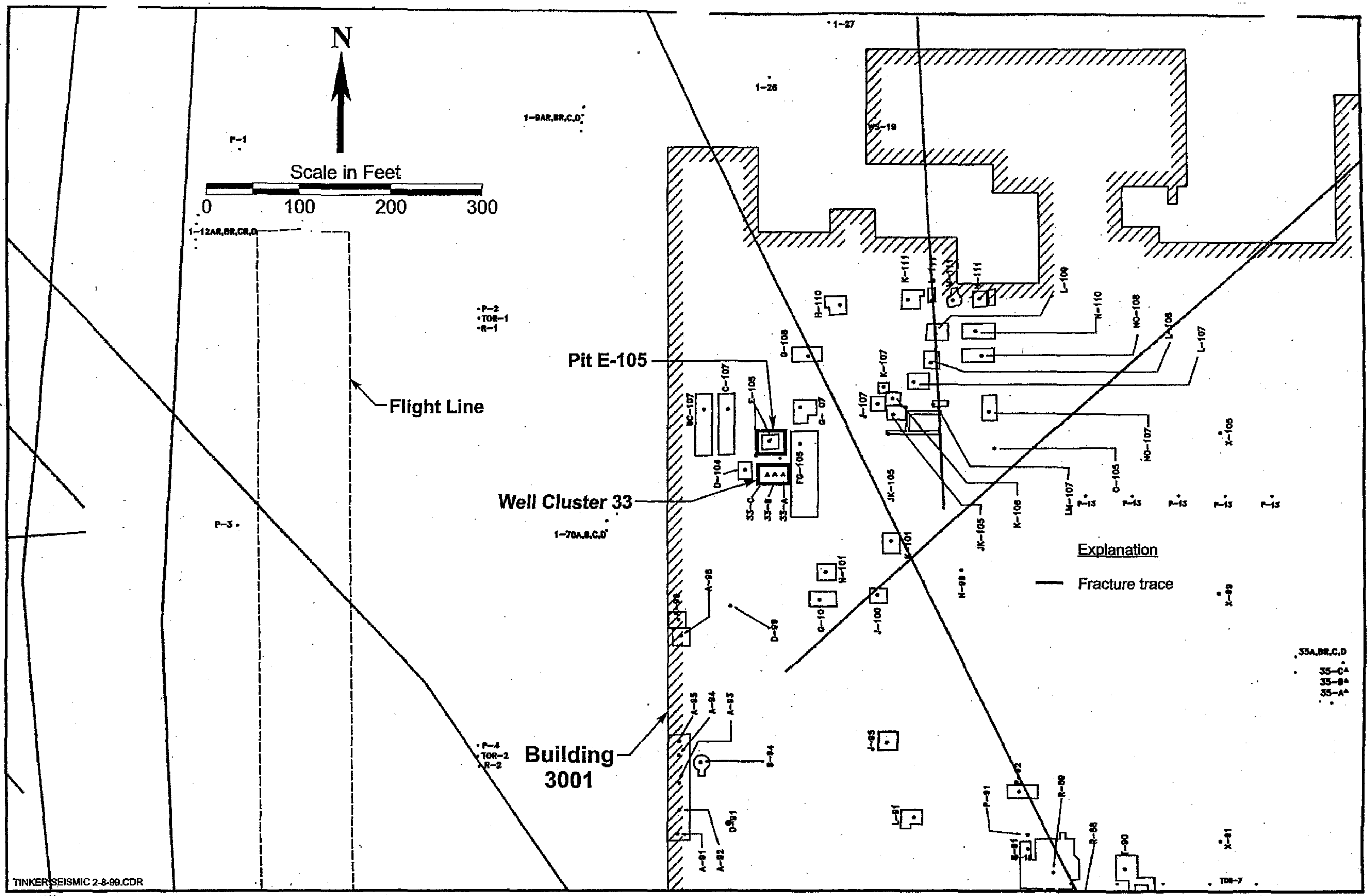


Figure 6. Demonstration Site Location at the North End of Building 3001 at Tinker AFB

monitoring well clusters initially installed within Building 3001 are also shown on Figure 6. Well cluster 33, which is located just south of Pit E-105, has been plugged and abandoned. Some of the highest levels of TCE groundwater under the northeast quadrant of the building were detected in well cluster 33.

From the 1940s through the 1970s, unlined subsurface pits and trenches within Building 3001 were used as storage reservoirs to contain industrial solvents and wastewater. During their 30-year period of operation, the pits and trenches leaked, perhaps continuously, allowing percolation of contaminants into subsurface soil, bedrock and groundwater. Downward migration of the contamination reached the top of the regional aquifers. The contaminant plumes reach a maximum depth of 175 ft and extend laterally over an area of about 220 acres within the groundwater. Primary contaminants at the site are TCE, chromium, benzene, PCE, lead, and nickel.

The Building 3001 site includes the building complex (covering 50 acres), the North Tank Area, Pit Q-51, and the surrounding areas encompassed by the lateral extent of the groundwater contaminant plume. The site is located near the northeast boundary of the Base and covers an area of approximately 220 acres. The surrounding area of Building 3001 does not lie within the floodplain and is not considered to be a wetland.

The Building 3001 complex houses an aircraft overhaul and modification complex to support the mission of the Oklahoma City Air Logistics Center. The primary industrial activities conducted in the building (since operations began in the early to mid-1940s) are aircraft and jet engine service, repair, and/or upgrading. Some industrial processes use or generate solutions containing solvents and metals similar to contaminants found in the underlying groundwater. Organic solvents were used for cleaning and degreasing metal engine parts. TCE was the predominant solvent used from the 1940s until the 1970s. The degreasing operations were conducted in concrete pits set below the floor level. In the early 1970s, PCE began to replace TCE as the predominant degreasing solvent, and the pits were replaced with aboveground degreasing systems (pit, piping, pumps, etc.). The subsurface pits were emptied and abandoned, typically by backfilling with sand and capping with concrete.

Wastewater from the plating shop and paint stripping operations contained high concentrations of solvents and heavy metals, particularly chromium. Other waste materials generated from plating, painting, and heat-treating activities contain both solvents and metals. Subsurface contamination occurred primarily by leakage from the subsurface pits and trenches, erroneous discharging of solvents or wastewater into storm drains, accidental spills, and/or improper connections between wastewater and storm drains.

In 1987, the Environmental Protection Agency (EPA) placed the site on the National Priorities List because of the contaminated groundwater and soil. A remedial investigation was conducted in accordance with in 1980 CERCLA. The remedial investigation, completed in January 1988, found that the primary contaminants at the site are TCE and chromium. However, PCE and 1,2 DCE have also been detected. The highest concentrations of contaminants beneath the building are in the upper saturated zone, where 330 ppm of TCE and 80 ppm of chromium were detected.

The DoD, U.S. EPA, the State of Oklahoma, and U.S. Air Force agreed on a remedy for the problem, and in August 1990 signed a Record of Decision (ROD) for the Building 3001 operable unit. In the ROD, a pump-and-treat system was selected as the preferred system to remove and clean up contaminated water under the site. The system uses extraction wells to withdraw the contaminated groundwater, which is treated at a plant built specifically for this purpose. Tinker's Groundwater Treatment Plant, which began in 1994, is designed to process 216,000 gallons of groundwater per day and uses an air stripper to separate volatile organic compounds from the groundwater. A secondary treatment process removes chromium through a precipitation/filtration procedure. Water leaving the plant is treated to below drinking water standards, then reused in industrial processes at Tinker AFB.

3.3 Site Characteristics

3.3.1 Alameda Point - Site Characteristics. Most of Alameda Point was built on artificial fill material dredged from San Francisco Bay, the Seaplane Lagoon, and the Oakland Channel. The hydraulically placed fill is comprised mostly of silty sand to sand, with clay and/or gravel, and contains wood, concrete, and metal. It was placed on Holocene Bay Mud. The fill is up to 40 feet thick in the western portion of the base, and thins to the east. It was hydraulically placed in a submarine environment over a period of 75 years, beginning in 1900. About 400 to 500 feet of unconsolidated sediments overlie Franciscan bedrock, according to boring logs from water supply wells installed as early as the 1940s. The Bay Sediment is the youngest of the naturally occurring formations, and consists of Bay Sand and Bay Mud. The Bay Sand is gray with green or blue colors, and is fine to medium-grained sand or sandy silt, loose to medium dense with shells. The Bay Mud is also gray with green or blue hues, grades from clay to clayey silt, is soft to medium stiff, and has a minor amount of shells. The Bay Sediments are 130 feet thick, and are thickest in a paleochannel that trends nearly east to west across the middle of NAS Alameda. This channel cuts across the northern part of Building 5, and is north of the source areas of concern in this investigation. Bay Sediments are thin or absent in the southeastern part of the base. These sediments were deposited during the Holocene Age in an estuarine environment by deposition in channels that were eroded into older underlying sediments.

The Merritt Sand is older than the Bay sediments and was deposited in the late Pleistocene to Holocene Age. The medium-grained sands are brown, with yellow and red iron oxide stains, and sometimes having minor clay deposits. They are dense to very dense. This aeolian unit is up to 70 feet thick, and has been partially eroded by the paleochannel.

Groundwater is encountered in borings between 5 and 10 feet deep, and flow is generally to the west and southwest. Two aquifers, which are continuous, underlie Alameda Point. The first water-bearing zone occurs in the dredge fill, about 5 or 6 feet deep. The deeper aquifer is found in the Merritt Sand. The Bay Mud is considered to be an impermeable layer that isolates the upper aquifer from the lower aquifer. Both aquifers are influenced by tidal fluctuations and are characterized by water problems associated with nitrates, saltwater intrusion, and naturally occurring mercury contamination from the bedrock formation. As a result, groundwater is not presently used as a water supply on Alameda Island.

3.3.2 Tinker AFB - Site Characteristics. Tinker AFB is located in the Interior Lowlands physiographic province on gently westward-dipping Permian redbeds. Bedrock units encountered at Tinker AFB include the Garber-Wellington Formation and the overlying Hennessey Formation. The Garber-Wellington Formation outcrops in Central Oklahoma and supplies much of the drinking water for residents of Oklahoma and Cleveland counties. The recharge area covers the eastern half of Oklahoma County including Tinker AFB, and the formation dips to the west about 15 feet per mile. The Garber Sandstone and Wellington Formations are hydrologically interconnected formations that are not easily distinguished from each other based on rock type, key beds, fossils, or hydrologic properties. The Garber-Wellington is about 900 feet thick in the study area, and consists of lenticular and interbedded sandstone, shale, and siltstone. Sandstone is orange-red to reddish brown, fine-grained, and poorly cemented. The grains are sub-angular to sub-rounded and composed of quartz. Shale is reddish brown and silty. Although present beneath all of Tinker AFB, the Garber-Wellington is overlain by the Hennessey Formation over the southern half of the Base. Sediments of the Garber-Wellington are deltaic in origin. Stream-deposited sands interfinger with marine shales, and individual beds vary from a few feet to about 40 feet in thickness. Sandstone averages about 65% of the formation, as determined from borings drilled at the Base. Because of shifting channels and changing currents during deposition, detailed correlation of lithologic units is only possible over short distances.

A north-south geologic section (shown in Figure 7) through the eastern portion of Tinker AFB and Building 3001 illustrates the three major water-bearing and transmitting units that underlie the northeast quadrant and the study area. Various hydrogeologic and modeling studies done at Tinker designate them as the upper saturated zone, lower saturated zone, and production zone. These zones are separated by two distinct shale units, the Upper and Lower Shale, that represent the most significant semi-confining units beneath the northeast quadrant of the Base. Layers 1 through 11 in Figure 7 represent the series of interbedded and interfingered shale and siltstone lenses that comprise the two distinct shale units. Together, all these units form the five primary hydrostragraphic units occurring within the northeast quadrant.

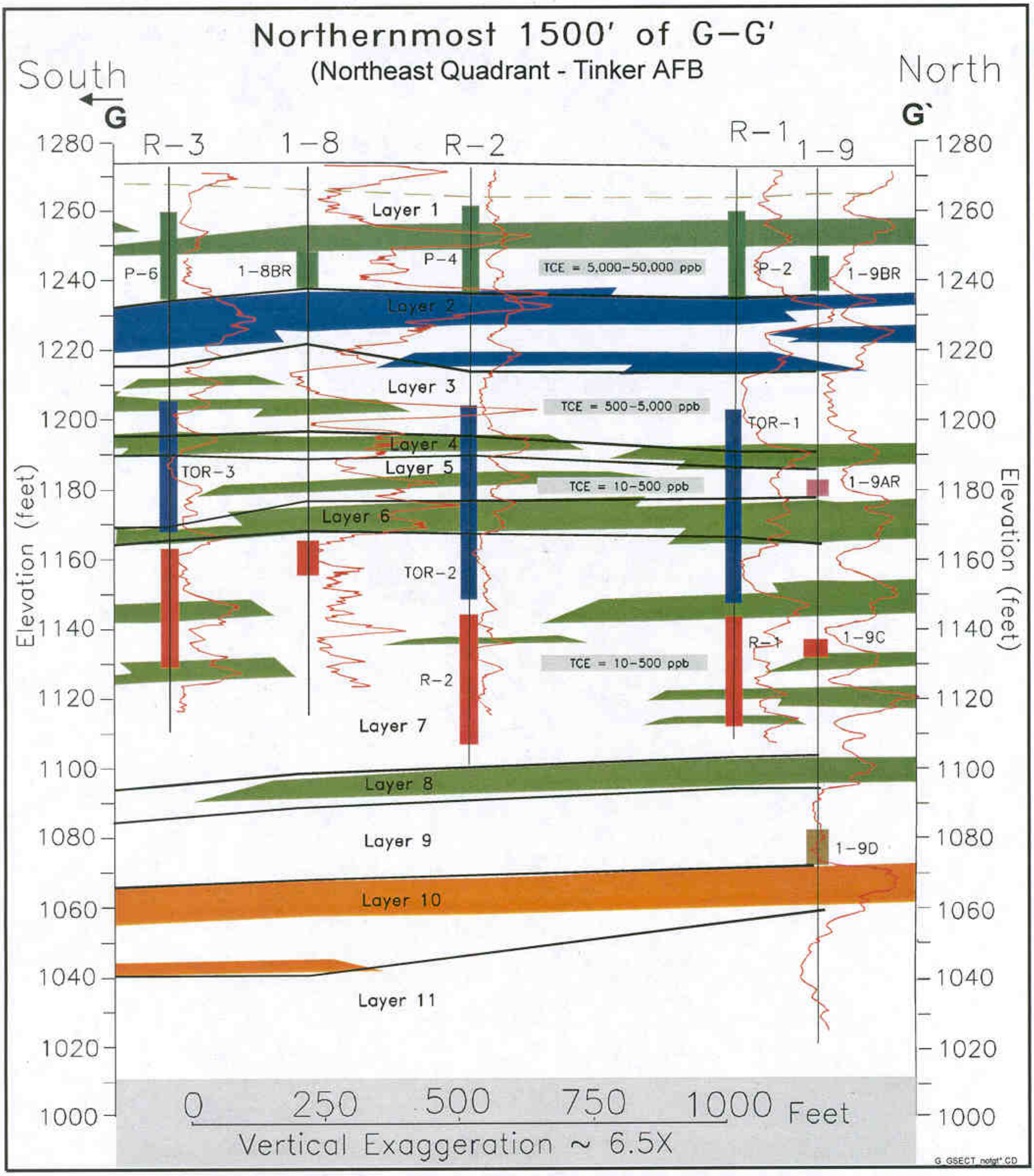
Figure 7 also indicates decreasing TCE concentrations with increasing depth below ground surface. The subsurface shale layers have prevented contaminants from migrating into the drinking water zone. The contaminants that migrated into the upper zones of the Garber-Wellington traveled through possible cracks or discontinuities in the shale layers. Overall, the shale layers are effective in slowing the migration of contaminants into the producing zone.

Groundwater exists in the Garber-Wellington under both confined and unconfined conditions, depending on the presence of overlying shale beds, and flows to the southwest. The Garber-Wellington Aquifer is a Class I Aquifer. This irreplaceable aquifer produces water used for the public water supply. There are 25 water supply wells located on the Base. These wells, which were drilled in the 1940s, provide 4 to 6 million gallons per day for use by the Base, making Tinker AFB the greatest user of groundwater in the area. These wells average 217 gallons per minute and consist of multiple screens from a depth of 250 feet to 700 feet. This zone, where most of the water for industrial and commercial use is pumped, is relatively permeable, and pump tests from wells in the towns of Norman and Edmond yield permeabilities about 10^{-3} cm/sec. The average depth to water in the producing zone is about 250 feet, which is about 200 feet lower than the regional water table. Thus, a vertical component of groundwater flow also exists. The water becomes salty near the base of the formation, and wells drilled through the freshwater zone have to be partially backfilled to be usable. Background water quality at Tinker AFB is best in the deeper strata. In general, heavy metals such as barium, cadmium, chromium, mercury, and silver are at or below detection limits. Arsenic is about 0.002 ppm, lead about 0.04 ppm, and selenium 0.002 ppm. Overpumping tends to increase the concentration of some of these metals, especially arsenic, selenium, and chromium. Chlorides, sulfates, and conductivities seem to be the lowest in the deeper strata, and highest in groundwater under water table conditions (Integrated Environmental Team of Tinker AFB, 1997).

The Hennessey Formation outcrops over the southern half of Tinker AFB. The Hennessey thins to the north and pinches out just south of Building 3001. It consists of reddish brown shale with beds of siltstone and silty sandstone. Where present, the Hennessey separates the regional water table in the Garber-Wellington from overlying perched water. There are several wells in the area producing minor amounts of water from the Hennessey, which are developed from one of the thin sandstone beds or from joints and fractures in the shale.

Most of the streams on the Base have some alluvial deposits unless their channels have been modified, such as East Soldier Creek. These deposits consist of unconsolidated sediments of sand, silt, and clay.

The thickness of these deposits in the surveyed region has not been determined. The alluvial deposits are water-bearing and are hydrologically connected to a perched water table which is found over most of the Base (Integrated Environmental Team of Tinker AFB, 1997).



Legend: Shale Siltstone Sandstone

Figure 7. North-South Geologic Cross Section G-G' at Tinker AFB

Section 4.0 DEMONSTRATION DESIGN

4.1 Performance Objectives

The objective of this project is to demonstrate that 3-D EM resistivity surveying is an effective method for performing high-resolution site characterization and subsurface DNAPL source detection and delineation. This objective will be considered met if 90% of the EM resistivity predictions for DNAPL contamination are verified to be correct. Truth, or validation data, will be based on analyses of physical samples (groundwater and soil) taken from within the surveyed regions after the resistivity models have been produced.

This demonstration project was accomplished by performing and evaluating 3-D EM resistivity surveys at two DNAPL sites. The data collected and processed from the EM surveys also was used to generate predictions for subsurface contamination and depths to stratigraphic features. The accuracy of the predictions was evaluated by comparing them with conventional site characterization data.

4.2 Physical Setup and Operation

This technology demonstration effort consists primarily of conducting two 3-D EM resistivity geophysical surveys and correlating these survey results with conventional physical samples.

A 3-D EM resistivity survey incorporates a complete review of all available and relevant geologic/hydrogeologic information as well as consideration for site-specific sources of cultural and electrical noise interference. This review is necessary to determine the most effective geophysical survey design with respect to source pattern and to placement of receiver wells in the surveyed area.

The EM resistivity survey method uses a surface source coil that transmits a very low frequency signal. This induces a long wavelength and time-varying magnetic flux below the source coil's location. The EM source is an optimally tuned coil having 32 turns of low resistance wire which create an area of 4 m^2. A current of up to 11 amperes runs through the coil, thus creating a maximum EM moment of 1,408 ampere-meters.

The induced magnetic field is remotely detected by the EM receiver located down-hole. The receiver is tuned to the specific source-signal frequency being used. This frequency is relatively low, 263 Hz, and is found at one of the minimum-amplitude spectral points of the noise spectrum to contend with cultural and industrial noisy sites. Figure 8 illustrates the data collection process. The signals from the receiver probe are passed through a High-Q inverted notch filter specific to the source-coil frequency. The collective effect of this system enhances the signal over noise. The filtered signal is then passed to an integrator, which performs additional signal-to-noise enhancement by summing and averaging the signal over many tens of cycles.

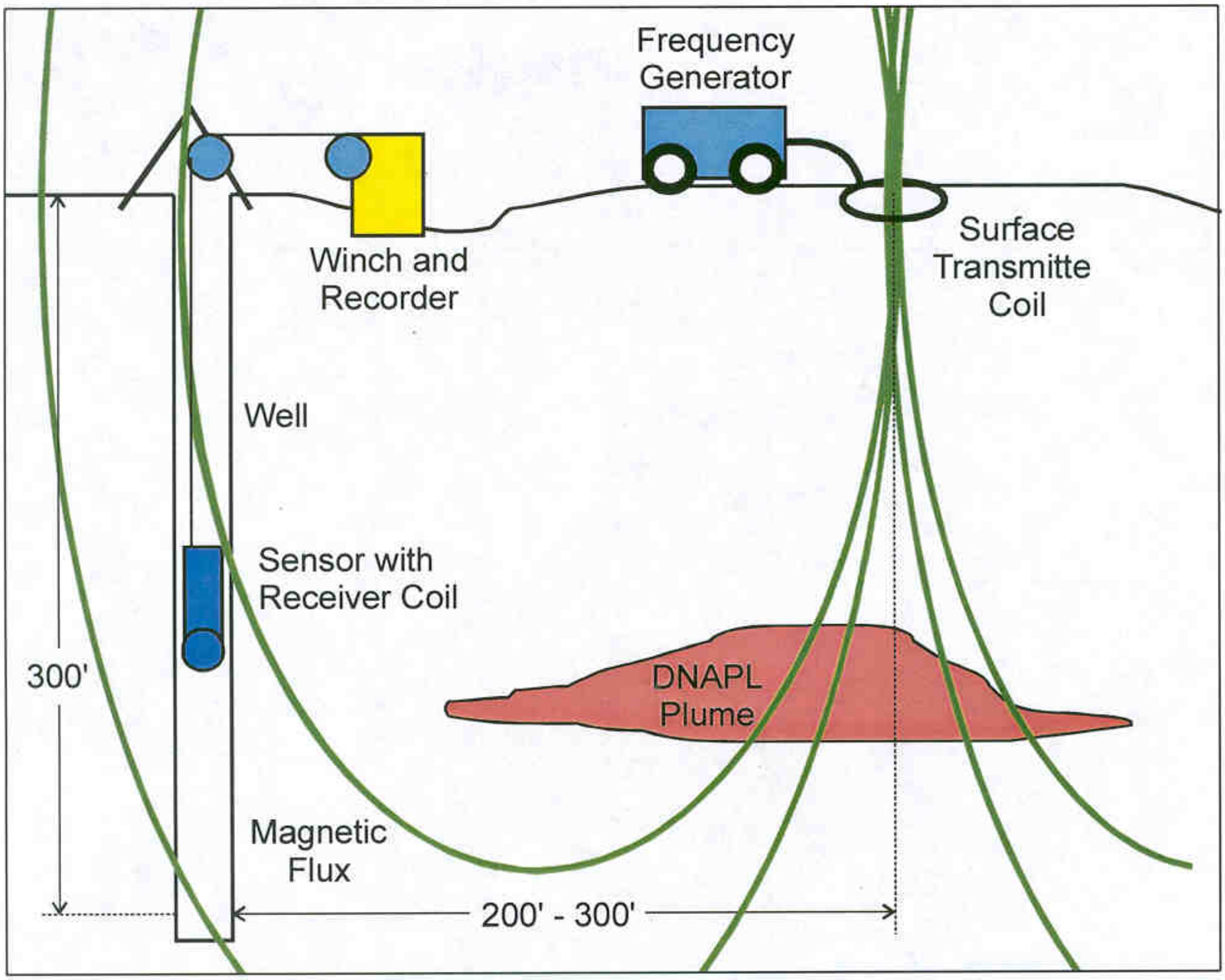


Figure 8. 3-D EM Resistivity Transmitter and Receiver System

Shown below are some general specifications of the basic system components.

Transmitter Loop	Receiver Probe	Data
Area = 43.1 feet^2	Length = 2.5 feet	16-byte A/D converter
32 turns	Diameter = 1.6 inches	1/100-scale resolution
11 amperes	30,000 turn; 28-gauge wire	263 Hertz

The voltage signals received at different depths in the well are the result of the superposition of time-varying magnetic fields from the surface coil and induced currents created in features of differing resistivity. The magnetic flux from the source coil is known as the primary flux, and the magnetic flux from the "eddy currents" is known as the secondary flux.

After a complete set of vertical offset log data representing the formations below the coil is recorded, the source coil is moved to another surface location and the process is repeated. Data acquisition at a site continues until the 3-D matrix of resistivity data collected is sufficient to meet the survey objectives.

The final phase of the field processing effort involves digital sampling of the integrated voltage output, plotting, and review of field records of the output for quality control. This is then followed by field evaluation of existing anomalies.

The digital data is stored on disc, and then undergoes the following processing off-site by GEHM Environmental:

- Automated editing and removal of extreme noise from the unusable data sets
- Automated amplitude static corrections to eliminate variations in the individual logs caused by changes in source strength in and around metal noise features (such as buried metal tanks, pipelines and plates).
- Adjustments to all data sets from each receiver well to conform to a data set that would have been acquired from a single receiver well. These adjustments are predicted by overlap data recorded from two or more receiver wells.
- Automated signal-to-noise enhancement using 0.1-foot samples to generate resolution for the final 0.5-foot offset logs that are input into the model process.
- Generation of one-dimensional log models, prior to three-dimensional processing.
- Bisect the one-dimensional logs into first-order (gross character) resistivity logs and second order (refined character, usually associated with geologic stratigraphy) residual logs.
- Design of two-dimensional and three-dimensional model weights.
- Three-dimensional surface-integral modeling.

The final data processing effort consisted of developing 3-D images, maps, and cross sections using Dynamic Graphics' software and annotation using Silicon Graphics' Showcase software.

A high-resolution 3-D EM resistivity survey was conducted at Site 5, Alameda Point, and at Building 3001, Tinker AFB, in September 1997 and January 1998, respectively, by GEHM Environmental Corporation. GEHM Environmental Corporation's name for these 3-D EM resistivity surveys is an Electromagnetic Offset Log (EOL).

4.2.1 EM Resistivity Data Acquisition and Analysis. The exact positioning of each survey grid was chosen based on review of all existing site characterization information, and discussions with the site environmental representatives. This ensured that each EOL survey was being performed in areas suspected or known to have significant concentrations of DNAPL in the subsurface. These surveys were accomplished with two instrumentation wells at each site, and each survey encompassed an area of approximately 2 acres, as shown in Figures 9 and 10. The EOL application provided 3-D resistivity data that was used in identifying the location of suspected DNAPL contamination within each survey grid. As mentioned in Section 2.1, contrasts in the resistivity data were measured and used to rank the probability of finding DNAPL contamination within a particular region. "Anomalous" areas represented regions of very high resistivity contrast. This large contrast was believed to be directly associated with the spatial distribution of DNAPL and/or other hydrocarbon based compounds within the vicinity. On the other hand, "average" resistive zones showed little to no resistivity contrast and were considered to be background areas having no DNAPL contamination. The accuracy of the predicted locations of DNAPL anomalies was validated with a physical soil and groundwater sampling program.

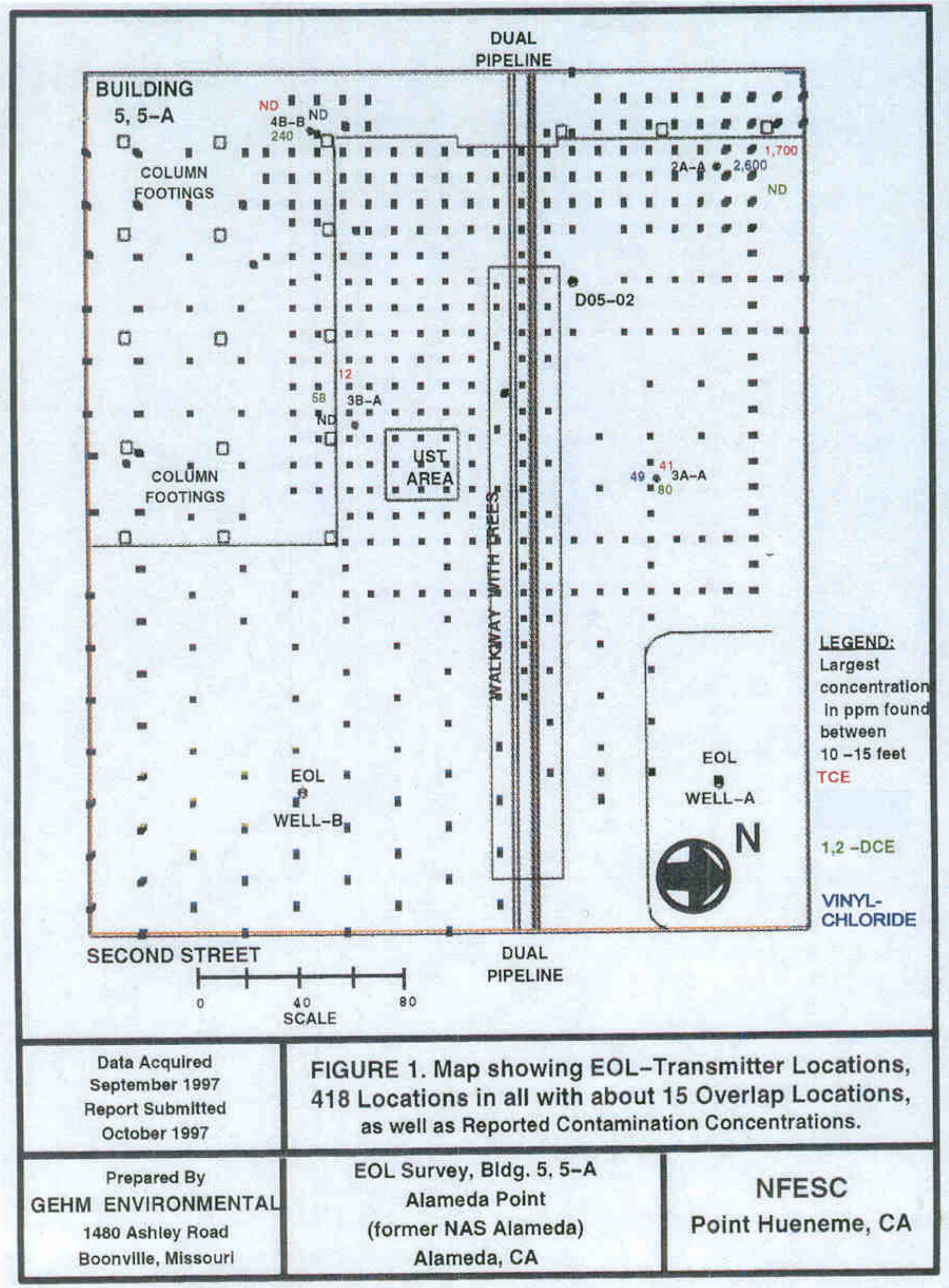
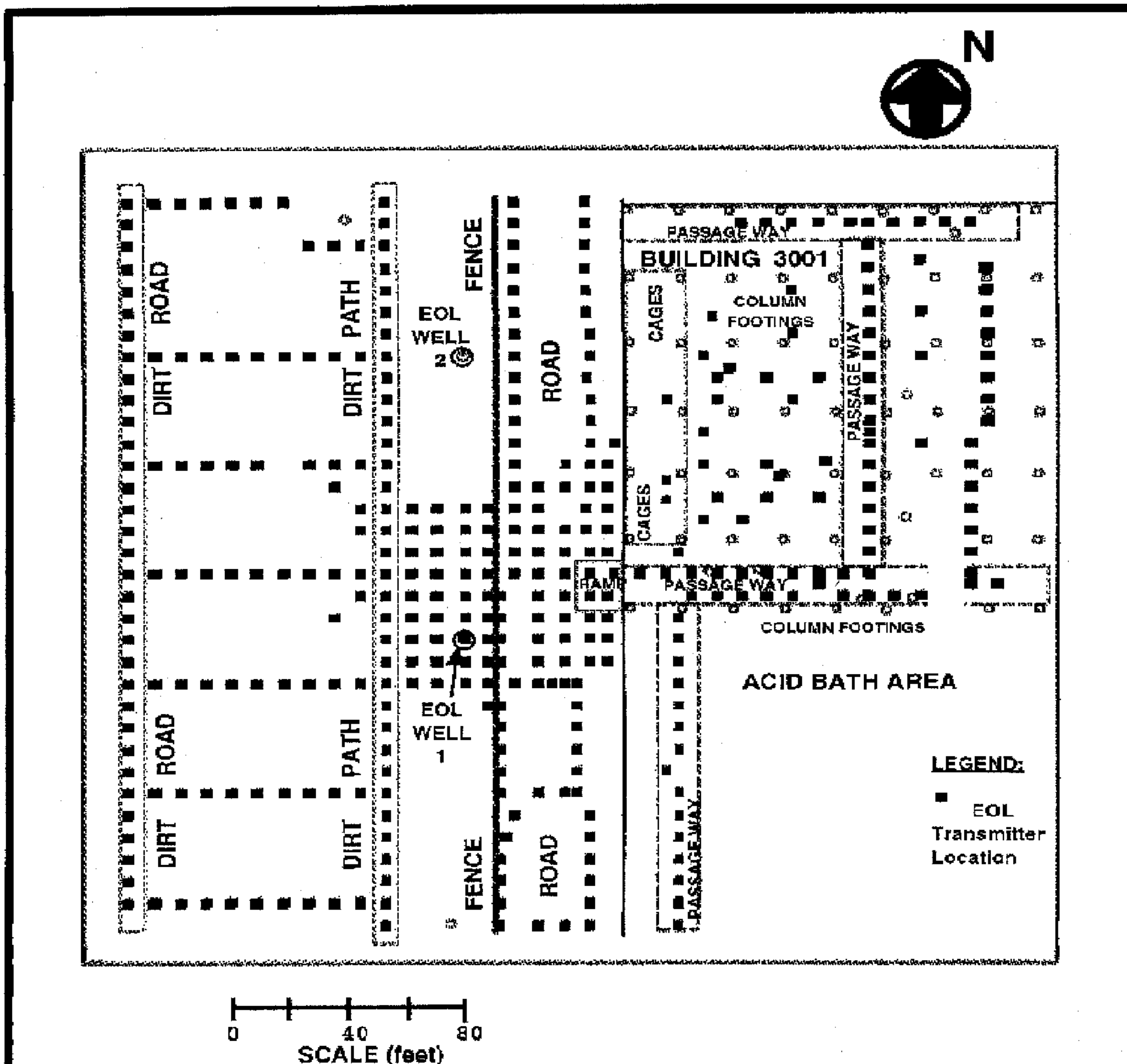


Figure 9. Transmitter Locations – Alameda Point



Data Acquired January 1998 Report Submitted February 1998	**FIGURE 5. Map showing EOL–Transmitter Locations, 400 Locations Including About 20 Overlap Locations.**

Prepared By GEHM ENVIRONMENTAL 1480 Ashley Road Boonville, Missouri	EOL Survey Building 3001 Tinker AFB Oklahoma	NFESC Point Hueneme California

Figure 10. Transmitter Locations – Tinker AFB

4.3 Validation Sampling Program

4.3.1 EOL Site Survey Reports. Following GEHM's application of the EOL technology at each site, an EOL resistivity site survey report was provided for each of the two demonstration sites. These reports, found in Appendix B, contained analysis and conclusions inferred and interpreted from the resistivity distribution and patterns of models and images developed from the raw data. The reports included: 1) site maps displaying the survey footprint with EOL transmitter stations and receiver well locations; 2) EOL resistivity image maps displaying resistivity contrasts at depth intervals; and 3) an EOL resistivity image map indicating suggested confirmation/ validation boring locations for a particular depth.

4.3.2 Validation Sampling Selection. Using GEHM's conclusions and recommendations, NFESC and the University of Missouri selected field validation targets to conclusively establish the accuracy of the EOL technology for each surveyed region. These target locations (with [x, y, z] location and depth coordinates) were selected based on their potential for validating the survey results with physical sampling proven to contain DNAPL or chlorinated volatile organic compounds (CVOC) contamination. A detailed account of each project's sampling plan may be found in the Technology Demonstration Plans for Alameda Point and Tinker AFB, included in Appendix B.

4.3.3 Validation Sampling Analysis. Groundwater and soil samples were collected at each target location. Analytical results from these physical samples were used to determine the presence of DNAPL.

When present as a separate phase, DNAPL compounds are generally detected at less than 10% of their aqueous solubility in groundwater. Typically, dissolved contaminant concentrations greater than 1% of the aqueous solubility limit are highly suggestive of NAPL presence. This relatively low value is due to the effects of a non-uniform groundwater flow, variable DNAPL distribution, the mixing of groundwater in a well, and the reduced effective solubility of individual compounds in a multi-liquid NAPL mixture. In addition, concentrations less than 1% solubility do not preclude the presence of NAPL (Cohen et al., 1993).

For this validation effort, a validation sample was considered to contain DNAPL if the lab analyses indicated levels of contamination of at least 10% of the contaminants' free-phase solubility in water. For example, the solubility of TCE = 1,100 mg/L (Pankow & Cherry, 1996) hence, for this effort, the presence of TCE as a DNAPL would be indicated by a TCE concentration greater than or equal to 110 mg/L (110 ppm). This measurement value is an order of magnitude greater than the established 1% "rule-of-thumb" value for DNAPL detection. The rigorous 10% solubility value was selected as a cutoff limit for DNAPL detection because this technology attempts to identify the actual subsurface DNAPL source zones.

4.3.4 Comparative Analysis. The accuracy and efficacy of the EOL technology was established by comparing the EM resistivity survey results to the field validation results. Findings from this correlation were categorized as true/false positives and true/false negatives. For example, a true positive reflects an EOL prediction that indicated the presence of DNAPL and was confirmed by a validation target sample at that location, to have DNAPL contamination. A finding of false negative occurred when an EOL prediction indicating little to no DNAPL in a specific area, was proven incorrect by a target sample taken from that area. The target sample had to have a DNAPL concentration greater than 110 ppm.

The last three relationships correspond to sites that are not contaminated with DNAPL. A false positive reflects a case where the EOL prediction indicates a medium or high level of contamination in an area known to have no DNAPL. A true negative corresponds to a low EOL-predicted DNAPL value for a sampling area that actually has little to no DNAPL. These relationships are shown in the list below:

Predicted EOL Resistivity Contrast[(a)]	Validated DNAPL Concentration	Correlation
Anomalous	[DNAPL] >110 ppm	true positive
High/Above Average	[DNAPL] >110 ppm	true positive
Average	[DNAPL] >110 ppm	false negative
Anomalous	[DNAPL] <110 ppm	false positive
High/Above Average	[DNAPL] <110 ppm	false positive
Average	[DNAPL] <110 ppm	true negative

(a) The following resistivity values were estimated to reflect a range of DNAPL concentrations.

Anomalous	> 110 ppm
High/Above Avg.	= 10 – 110 ppm
Average	= 0 – 10 ppm

4.4 Technical Performance Criteria

4.4.1 Contaminants. This project was directed towards locating subsurface DNAPL contamination source zones. Of particular interest are TCA, TCE, DCA, DCE, 1,2 DCE, PCE, chloroethane, and vinyl chloride compounds. For the validation effort, an analytical result of a target sample was considered a positive DNAPL presence if the cumulative level of contamination in a sample was at least 110 ppm. For example, an analytical result of 30 ppm TCE and 80 ppm TCA would indicate the presence of DNAPL. An analytical result was considered a negative DNAPL result if: 1) the cumulative concentration of the DNAPL constituents was less than 110 ppm; or 2) none of the constituent concentrations exceeded their maximum contaminant limits (MCLs) as established by the EPA.

Validation sampling at Alameda Point confirmed the presence of fuel hydrocarbons in the subsurface, in addition to DNAPLs. The intermixing of DNAPLs and other hydrocarbons does not negatively impact the EOL technology's ability to detect and delineate a commingled plume. However, it is possible that an intermixed anomaly could lead to a false positive detection for DNAPL. An anomaly containing significant hydrocarbon contamination and small DNAPL constituent concentrations will have a noticeable resistivity contrast. As a result, it will be depicted in the EM survey as an area with a high probability of having DNAPL present. Unfortunately, verification sampling analysis for DNAPL constituents will reveal a cumulative DNAPL concentration far less than 110 ppm. A methodology to correct for the presence of intermixed hydrocarbons in an EM survey has yet to be successfully developed.

4.4.2 Process Waste. There was no process waste generated during EM resistivity data collection. IDW consisted of the washdown water used to decontaminate the well drilling equipment, the Geoprobe® and SCAPS probes, and the samplers after use, as well as the cuttings generated from drilling the receiver wells. All IDW was contained in 55-gallon drums and was disposed of in accordance with RCRA regulations.

4.4.3 Reliability. Equipment necessary to collect and store 3-D EM resistivity data is designed for field use. If an equipment failure were to occur, the failed component could be replaced within 24 hours.

4.4.4 Ease of Use. The use of this EM resistivity equipment requires three qualified individuals. The actual operation is typically facilitated by a source operator who moves the transmitter coil from grid point to grid point to allow for the flux to be generated in the subsurface below the grid point. A second individual, the recording engineer, located in the vicinity of the receiving well some distance from the transmitter, performs the collection and logging of the data from the grid point. Both functions are essentially trouble-free once up and running, and can be configured in a variety of ways to accomplish the logging for a particular site. The EOL data interpretative analysis is performed by a third, highly qualified geophysicist with considerable experience in reviewing geological/hydrogeological information and interpreting and modeling EM resistivity data.

4.4.5 Versatility. This method can be used for imaging subsurface components with high resistive characteristics as well as imaging subsurface stratigraphic features. Additionally, it can be used for remediation monitoring and post-remediation verification. Other features that make this technique extremely versatile are: it is nonintrusive except for one or two borings which must be drilled in noncontaminated areas; it greatly reduces the amount of drilling and sampling; it is less disruptive; and, it can be performed in most structures and over most surfaces.

4.4.6 Off-the-Shelf Procurement. There are several geophysical firms that use EM methods for various purposes in the environmental industry. However, the unique data processing steps employed by GEHM to refine and improve the accuracy of EOL modeling techniques are proprietary to the EOL process. This technique improves the ability of EOL to accurately image subsurface anomalies.

4.4.7 Maintenance. For the most part, very little maintenance is required for the operation of the EOL technology. Most of the field components rely on solid-state electrical equipment that is durable and trouble-free. Some of the surveying components are disposable and easily replaceable. All of the equipment is continually monitored for optimum performance.

4.4.8 Scale-Up Issues. The equipment employed for this demonstration has been used on several DoD programs, and as such, the scale-up issues do not apply.

4.5 Sampling and Analytical Procedures

4.5.1 Selection of Analytical Laboratories. Tetra Tech was selected to subcontract with analytical laboratories for the chemical analyses of physical samples collected in the field at Alameda Point. They are local contractors to Alameda Point, and have been used successfully in the past to provide analytical services in support of base investigation efforts. Tetra Tech subcontracted with American Environmental Network to perform the analyses. Southwest Laboratory of Oklahoma was selected for performing chemical analyses of soil and groundwater samples collected in the field at

Tinker AFB. They are local to central Oklahoma, and have also been used successfully in the past to provide analytical services in support of Base investigation efforts at Tinker AFB.

4.5.2 Selection of Analytical Method. The primary method used to validate DNAPL predictions based on EM resistivity survey was to compare the predictions to results derived from chemical analyses of samples taken at the site. Samples analysis was performed using a gas chromatography/mass spectrometry (GC/MS) in accordance with EPA Method 8260, capillary column technique. This method identifies the presence of DNAPL compounds in the physical samples and quantifies their level of contamination.

4.5.3 Sample Collection. Groundwater and soil samples were collected to support the validation of the EM resistivity survey results. Because soft unconsolidated sediments are found in the upper fill layer at Alameda, it was possible to replace the more disruptive rotary drilling method with a much more productive hydraulic push probe for sample collection. This also enabled collection of discreet, representative samples at the locations and depths of interest. At Tinker AFB, the company AEI/B. Graham, Inc., was the drilling company under contract to JMB Associates of Owasso, OK. At Tinker AFB, rotary drilling was used to sample subsurface soil and groundwater.

The *Three-Dimensional Resistivity Survey EOL Reports* produced by GEHM Environmental and found in Appendix B, provided subsurface interpretive analyses, with conclusions and recommendations for target validation locations based on anomalously high (indicating DNAPL) resistivity features. A select number of these target locations were chosen for verification drilling and sampling.

At Alameda, each sampling push location was identified in the field by referencing the EM survey grid points, which were marked on the ground. Each push location was measured to within ±0.5 foot from the target location. The depth of the collected sample was measured by the instrumented cone penetrometer testing (CPT) rig. Each sampling depth was measured to within ±0.1 foot of the target depth. At Tinker AFB, samples were collected using conventional drilling techniques. Locations were accurate to within 1 foot.

4.5.3.1 Water Sampling. Water sampling is performed with the BAT® water sampler, which consists of a 40-milliliter (mL) tube with a rubber cap. This chamber (under vacuum) is pushed down into the ground to the desired depth, at which point a syringe needle punctures the lid and allows groundwater within the aquifer present at that depth to flow into the tube. The needle is then retracted, and the sealed tube is brought back to the surface. All samples collected in this manner are sent to the laboratory sealed in their original collection tube.

4.5.3.2 Soil Sampling. At the Alameda site, soil samples were obtained by driving a 1.5-inch-diameter, 24-inch-long split spoon sampler into the ground at the designated depth. Upon recovery of the split spoon sampler to the surface, a small amount of soil was removed from the sample core and put into a 40-mL volatile organic analysis (VOA) vial. The vial was pre-filled with 15 ml of reaction-grade methanol in order to minimize the amount of volatilization that could occur in the sample container. This allowed for a more accurate analytical result. The vial sample taken from the core section was selected on the following criteria:

- Section contained visible staining (from contamination)
- Section had a high, localized flame ionization detector (FID) reading
- Section had an interface between coarse-grain material and fine-grain material
- Taken 1 cm from the bottom of the sample core.

All samples collected in this manner were sent to the laboratory in their sealed VOA vials.

The sampling method at Tinker AFB involved collecting samples from drill cuttings at pre-assigned depths. Neither the FID instrumentation nor the methanol preservation methods were used. All soil samples were placed in vials and stored in a small refrigerator and then transferred to an ice-chilled cooler prior to overnight shipment to the lab.

4.5.3.3 ***Experimental Controls.*** Rigorous quality assurance practices are required when evaluating contaminant concentration levels near their maximum contaminant level thresholds (i.e., 5 ppb for TCE). However, due to the gross nature of the criteria for identifying DNAPL (i.e., constituent concentration >110 ppm), such measures are not necessary. The following Quality Assurance and Quality Control (QA/QC) measures were followed for each sampling interval at the two sites.

The rinseate water from the sample collection equipment was analyzed prior to investigation at each new validation location. This ensured that no residual contamination from a previous sample remained on the apparatus.

One duplicate sample was made from one of every ten samples collected that was associated with a high confidence prediction for containing DNAPL. This ensured adequate repeatability and resolution of the laboratory analytical results, using samples that most likely had contamination.

Also, for each high confidence target, a duplicate sample was made and analyzed at the on-site laboratory and at an off-site laboratory. This provided an indication of the accuracy of the on-site lab's results.

One trip blank was included with the samples sent to the off-site laboratory. Due to the proximity of the on-site laboratory and the gross nature of the criteria for identifying DNAPL constituents in most of the samples (i.e., 110 ppm), trip blanks were not included with samples analyzed on-site.

4.5.4 Sample Analysis. Water samples are analyzed in accordance with EPA Method 8240, while soil samples were analyzed by EPA Method 8260/8270 VOC by gas chromatography/mass spectrometry (GC/MS): capillary column technique. Since the contaminant levels of interest are in excess of 110 ppm concentration, this application only requires an instrument detection limit (IDL) of >1 ppm.

Water samples received at the lab were transferred to a separatory funnel and allowed to sit for 10 minutes. Afterwards, 10 mL was drained from the bottom and used for chemical analysis. For soil samples, approximately 10 g of soil was taken from the storage vial and used for chemical analysis.

The lowest instrument range for the GC/MS method is 5-200 ppb. This range was scaled up by diluting the samples. The instrument range for analyzing the samples associated with high confidence of DNAPL encompassed 10-400 ppm concentrations. This corresponds to an instrument resolution of +/- 5 ppm on the upper end of the scale.

Samples were also inspected visually for DNAPL. This was accomplished by adding a small amount of hydrophobic dye (Sudan IV or Oil Red O) to the remaining sample water (for soil samples: soil sample + equal volume water). The mixture vial was shaken by hand and observed for signs of separate phase product.

Section 5.0 PERFORMANCE ASSESSMENT

The objective of this task was to evaluate the likelihood that 3-D EM resistivity technique is capable of consistently finding DNAPL.

Where present as a separate phase, DNAPL compounds generally are detected at less than 10% of their aqueous solubility in groundwater. Typically, dissolved contaminant concentrations greater than 1% of the aqueous solubility limit are highly suggestive of NAPL presence. This relatively low value is the result of the effects of non-uniform groundwater flow, variable DNAPL distribution, the mixing of groundwater in a well, and the reduced effective solubility of individual compounds in a multi-liquid NAPL mixture. In addition, concentrations less than 1% solubility do not preclude the presence of NAPL (Cohen et al., 1993).

Validation is the process of confirming that a target identified by the EM survey as potentially containing DNAPL does in fact actually contain DNAPL. A target location is selected in this area, and drilling, groundwater sampling, and chemical analyses of the soil and groundwater are performed to validate the EM survey prediction.

Sampling data indicated the presence of DNAPL if the level of contamination in a sample was at least 10% of the product's solubility in water. For example, the solubility of TCE in water is 1,100 mg/L (Pankow and Cherry, 1996); hence, for this effort, the presence of TCE as a DNAPL would be indicated by a TCE concentration greater than 110 ppm. This measurement value is an order of magnitude greater than the established 1% "rule-of-thumb" value for DNAPL detection. Along with the collection of physical samples, the wells were logged to evaluate the accuracy of the stratigraphy predicted for the target locations.

An overall review of the results validating the EOL technology show that, at Alameda Point there were no true positives, 20 true negatives, 18 false positives, and 1 false negative. At Tinker AFB there were no true positives, 4 true negatives, 14 false positives, and 2 false negatives. In summary, not once was the EOL technology able to predict and then confirm the presence of DNAPL in the subsurface. In 32 cases, a high or medium confidence rating was predicted in finding DNAPL, yet validation sampling revealed little to no DNAPL concentrations. In 24 attempts, the technology accurately predicted the absence of DNAPL in a specified area. And in 3 cases, DNAPL was detected at a minimum of 110 ppm in a location predicted to have little to no hydrocarbon contamination. The following chart reflects the overall performance of the EOL technology.

Summary of EM Resistivity Performance Results

	# of Target Locations Predicted to Have DNAPL w/ Confidence of	
	High or Medium	**Low**
DNAPL Found @ Targets (a)	Alameda = 0 Tinker = 0	Alameda = 1 Tinker = 2
DNAPL NOT Found @ Targets (b)	Alameda = 18 Tinker = 14	Alameda = 20 Tinker = 4

(a) Total DNAPL concentration in soil/groundwater samples taken from target locations measures > 110 ppm.

(a) Total DNAPL concentration in soil/groundwater samples taken form target locations measures < 110 ppm.

5.1 Validation Data

Validation data were collected and evaluated during drilling and sampling at a number of attribute anomalies indicated by the EOL data and suspected to be the result of DNAPL. Interpretations of the EOL data in conjunction with the geologic model led to identification of structural elements and key anomalies, which are possible pathways and traps for DNAPL. Predictions for the presence of DNAPL at the target anomalies were evaluated against the 10% solubility limit for the respective contaminants.

The areas (anomalies) proposed for investigation were referred to as targets or target sample locations. Site survey grids were used to illustrate the location of a target sample. A sample location was defined by coordinates from a designated benchmark and depth below ground surface.

The targets were assigned a high, medium, or low confidence of encountering DNAPL. This qualitative ranking was based primarily upon the measured resistivity contrasts of anomalies visible at the site. The proximity of an anomaly to a source, fill, and any man-made structures or features was also considered. The EM Resistivity Image Maps provided by GEHM (see Appendix B), displayed resistivity contrasts at varying depth intervals below ground surface. The resistivity contrasts were displayed as Anomalous/High Resistivity regions, Above Average resistivity areas, and Average or background resistivity. The anomalously high resistivity zones were believed to be directly associated with the presence of DNAPL solvent compounds, and therefore given a high confidence prediction of finding contamination in that area. Average or background resistive zones were associated with the absence of compounds and thus labeled with a low confidence level. the following chart summarizes this classification process.

Confidence of Finding DNAPL	Size of Resistivity Anomaly
High	Anomalous/High
Medium	Above Average
Low	Average

5.2 Data Assessment

During the data acquisition process in the field, the 3-D EM resistivity logging operator views a computer monitor which simultaneously shows voltage, depth, and the logarithm of 1/voltage. An ASCII file is generated from each data log, which consists of depth (feet), receiver speed (feet/minute), receiver voltage (millivolts, mV), transmitter current (milliamps, mA), and the logarithm of 1/V. Each of these logs is associated with a transmitter location (X, Y coordinates) and a particular receiver well.

The ASCII files are edited in the field by the logging operator who generates a set of data log files. These logs consist of an X,Y,Z coordinate location (feet), resistivity horizontal affect (RHOA) measured in ohm-meters (ohm-m), RHOA1 (ohm-m), and RHOA2 (ohm-m). The RHOA is taken from the original logarithm of 1/voltage. RHOA1 is a first-order apparent resistivity, which describes significant resistivity changes. RHOA2 is a second-order apparent resistivity, and is the difference between the original RHOA and the RHOA1.

The final data log processing consists of generating second-order resistivity (RHOA2) and smoothed second-order resistivity (SRHO2) values. This is then incorporated into the final database of the resistivity logs consisting of the following information:

X, Y, Z location	LOG_{10} of 1/V	RHOA1 (ohm-m)	RHOA2 (ohm-m)	RHO2 (ohm-m)	SRHO2 (ohm-m)	current (mA)	transmit location	receiver well

This final data set is then incorporated into a 3-D visualization process. This is accomplished using Dynamic Graphics, of Alameda, CA, 2D/3D reservoir modeling software for final 3-D modeling and imaging.

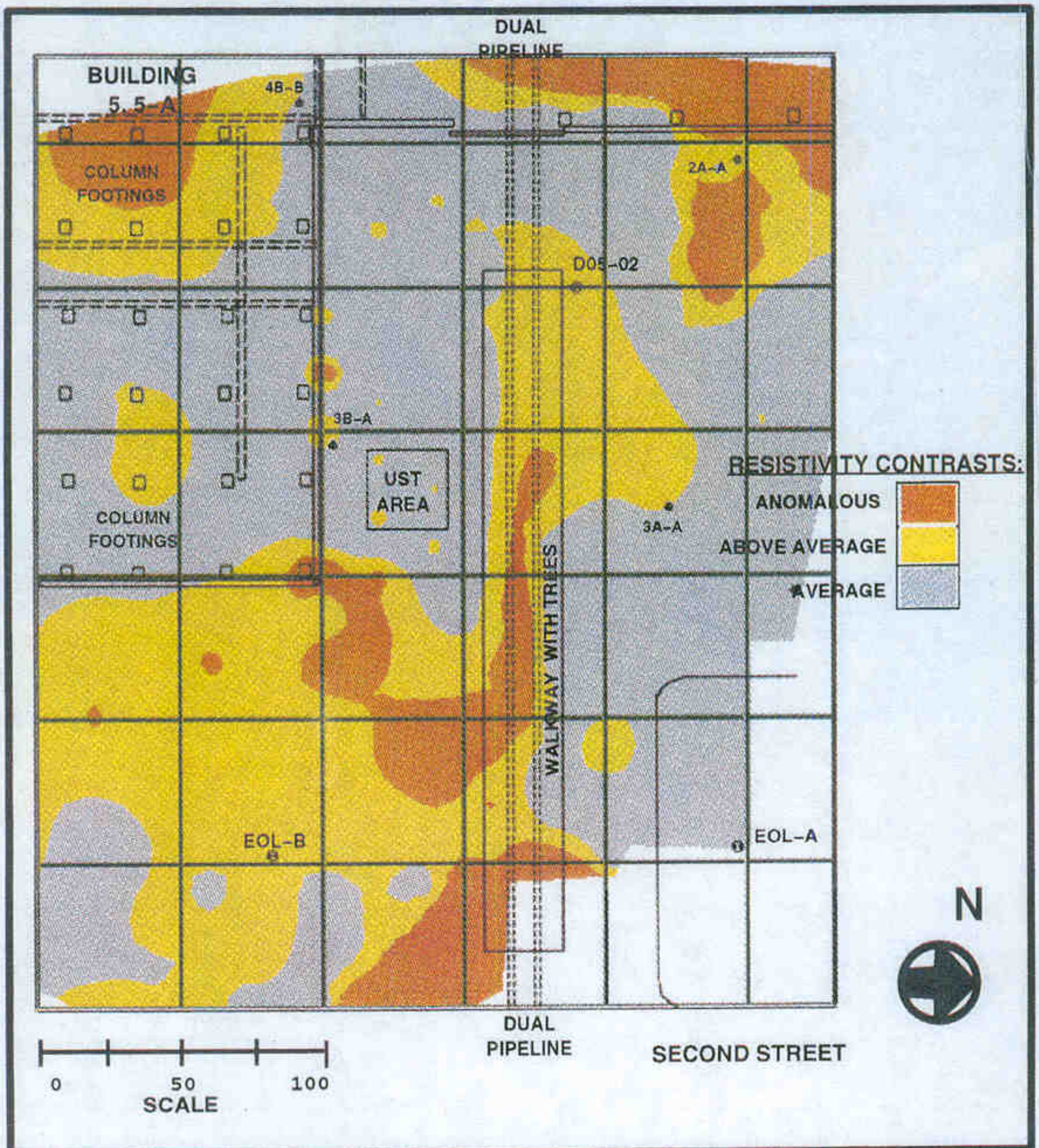
5.2.1 Alameda Point Building 5 and 5A. A 3-D model was generated for the Alameda site based on the subsurface resistivity properties found within the surveyed volume. Figure 11 contains a horizontal slice from the 3-D site model showing the resistivity contrasts found at 27 feet below ground surface (bgs). This image contains the most significant high resistivity anomalies found at this site, situated at a depth of 27 feet. Additional maps showing resistivity contrasts at various depths are contained in GEHM (1998a) which is included in Appendix B.

The list of predicted target locations in Table 2 were developed and included within the EM resistivity site survey reports provided by GEHM Environmental (See Appendix B). Each sample reflects the confidence of DNAPL presence at a particular location and depth as interpreted from the EM resistivity surveys. GEHM recommended that validation sampling be performed at these locations using either the University of Missouri's GeoProbe unit, or NFESC's SCAPS truck. The number of targets identified by GEHM to be considered for validation exceeded the actual number of validation samples to be collected at each site by the University and NFESC. This allowed flexibility in selecting locations based on their ease of access. At the Alameda site, a direct-push technique was used. Since the direct-push method can acquire more samples for an allotted cost, more target locations were selected for sampling. The recommended target sampling locations, designated by the coordinates listed in Table 2, are depicted in Figure 12.

The initial field validation sampling effort was accomplished in November 1997, and a follow-on effort was performed in March 1998. The recommended QA/QC validation tasrget locations are shown on Figure 12. Locations for the access wells for the EOL receiver are also shown on Figure 12 and are identified as "EOL Well-A" and "EOL Well-B."

The sampling target points shown in Figure 13 represent the actual locations selected by the University of Missouri and NFESC to perform validation/truth sampling and analysis. These post survey sampling targets were completed with SCAPS and GeoProbe microwell techniques. Validation sampling locations were selected based on EOL resistivity contrasts that indicated regions of anomalous properties situated at the depth of the confining layer.

Table 3 lists the analytical results of the selected validation target samples shown in Figure 13. All data represented in Table 3 were collected at the Alameda site from project validation efforts conducted after the EM survey. Also shown in the table are each sample's relative coordinate location in relation to the machine shop located within the site survey grid.



Data Acquired September 1997 Report Submitted October 1997	FIGURE 4. Map of Resistivity Contrasts at About 27 Feet Below Grade

Prepared By GEHM ENVIRONMENTAL 1480 Ashley Road Boonville, Missouri	EOL Survey, Bldg. 5, 5-A Alameda Point (former NAS Alameda) Alameda, CA	NFESC Point Hueneme, CA

Figure 11. Map of Resistivity Contrasts at ~27 Feet Below Grade
EOL Survey, Alameda Point, CA

Table 2. GEHM's Suggested Locations to Perform Validation Sampling at Alameda Point

Site	Sample	Distance from Benchmark*		Ft bgs	DNAPL Presence
		X	Y		Confidence
Recommended Sample Locations to be Validated by University of Missouri					
B1	1	320	375	14-16	High
B1	2	320	375	26-28	High
B1	3	320	375	32-34	High
B2	4	355	365	14-16	High
B2	5	355	365	26-28	High
B2	6	355	365	32-34	High
B3	7	340	320	14-16	High
B3	8	340	320	26-28	High
B3	9	340	320	32-34	High
B4	10	310	330	14-16	Low
Recommended Sample Locations to be Validated by NFESC					
5	11	340	370	14-16	High
5	12	340	370	26-28	High
5	13	340	370	32-34	High
6	14	130	340	14-16	High
6	15	130	340	26-28	High
6	16	130	340	32-34	High
7	17	210	165	14-16	High
7	18	210	165	26-28	High
7	19	210	165	32-34	High
8	20	220	315	14-16	Low
9	21	230	230	14-16	High
9	22	230	230	26-28	High
9	23	230	230	32-34	High
10	24	260	105	14-16	High
10	25	260	105	26-28	High
10	26	260	105	32-34	High
11	27	230	65	14-16	High
11	28	230	65	26-28	High
11	29	230	65	32-34	High
12	30	315	205	14-16	Low

*The main benchmark is at the south extent of the west side of 2nd Street within the test area, and has arbitrary coordinates of X=100', Y=100'. The orientation is with the X value increasing from south to north, and the Y value increasing from east to west (locations in feet).

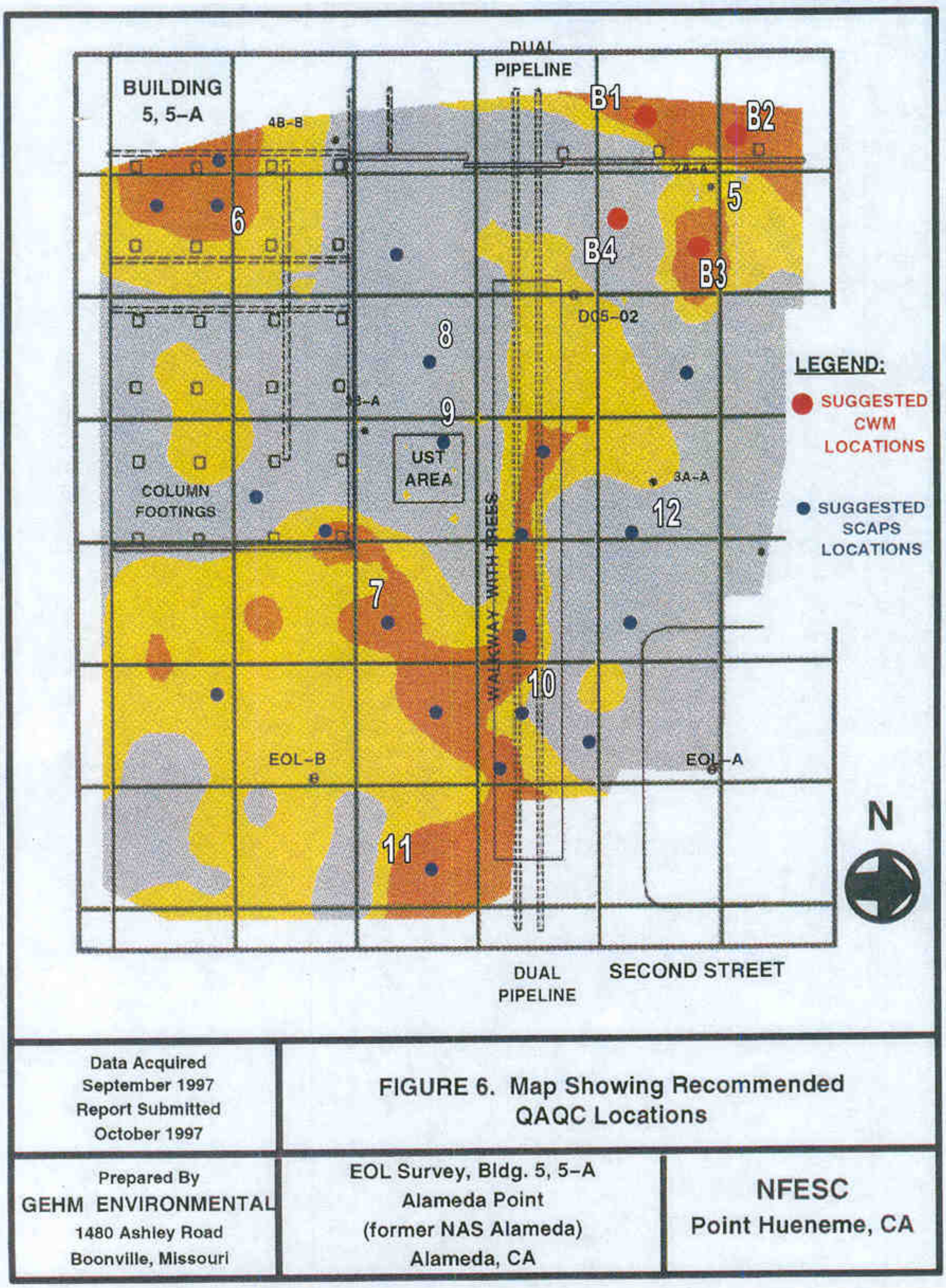
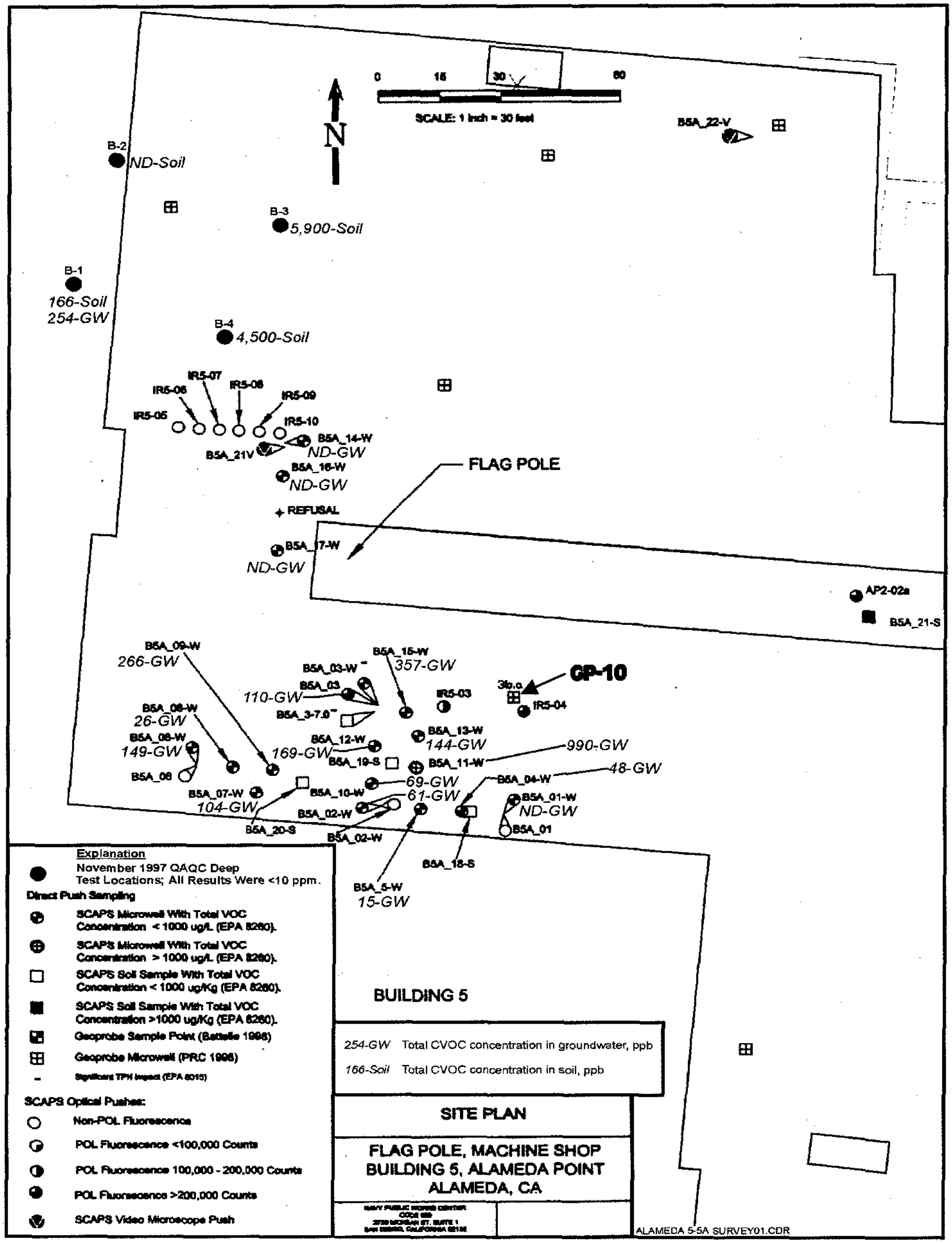


Figure 12. Map Showing GEHM's Recommended Validation Sampling Locations EOL Survey, Alameda Point, CA



(Note: Map is rotated 90° from Figure 11)

Figure 13. Map of Validation (Target) Sampling Points at Alameda Building 5

Table 3. Analytical Results of Samples from within Alameda Survey Grid

Sample I.D.	Well Location from bldg corner (machine shop) ft N/S	ft E/W	Screen/ Sample Depth	Analytical Results (DNAPLs) in ppm	Comments
landmark	0 N	0 W			
north edge	180 N				N side of survey grid
south edge	100 S				S side of survey grid
east edge		150 E			E side of survey grid
west edge		170 W			W side of survey grid
B-1	120 N	175 W	15	2-5	U of MO #1 initial sample
B-2	155 N	165 W	15	2-5	U of MO #2 initial sample
B-3	140 N	120 W	15	2-5	U of MO #3 initial sample
B-4	110 N	130 W	15	2-5	U of MO #4 initial sample
B5A-01	7.0 N	51.5 W	25-35	ND	SCAPS; LIF/soil log
B5A-02	7.0 N	81.5 W	25-30	.006	SCAPS; LIF/soil log
B5A-03	33.5 N	84.0 W	11-21	.110	SCAPS; LIF/soil log
B5A-04	7.0 N	61.5 W	15-20	.048	SCAPS
B5A-05	7.0 N	71.5 W	10-20	.015	SCAPS
B5A-06	15.0 N	129.0 W	10-15	.149	SCAPS; LIF/soil log
B5A-07	8.5 N	112.5 W	10-15	.104	SCAPS
B5A-08	15.0 N	119.0 W	20-30	.026	SCAPS
B5A-09	15.0 N	109.0 W	10-15	.266	SCAPS
B5A-10	13.0 N+	84.0 W	10-15	.069	SCAPS
B5A-11	18.0 N	73.5 W	20-30	.990	SCAPS
B5A-12	23.0 N	84.0 W	10-15	.169	SCAPS
B5A-13	26.5 N	73.5 W	10-15	.144	SCAPS
B5A-14	103.5 N	112.0 W	30-40	ND	SCAPS
B5A-15	34.0 N	84.0 W	5-10	.357	SCAPS; (+12 PPM TPH)
B5A-16	93.5 N	112.0 W	39-44	ND	SCAPS
B5A-17	73.5 N	112.0 W	39-44	ND	SCAPS
B1-S	96.5 S	18.0 E	5-10	30	SCAPS; south edge of survey grid
B3-S	72.0 S	75.0 W	21-31	.055	SCAPS; inside machine shop, by column
B5A-18S	7.0 N	60.0 W	30-31	ND	SCAPS; soil sample
B5A-19S	18.0 N	80.0 W	28-29	ND	SCAPS; soil sample
B5A-20S	12.0 N	100.0 W	26-27	ND	SCAPS; soil sample
GP-10	100 S	34 E	5-10	109	Geoprobe; south edge of survey grid
GP-11-01	23.0 N	73.5 W	25-30	ND	
GP-11-02	13.0 N	73.5 W	25-30	ND	
GP-11-03	18.0 N	78.5 W	25-30	ND	
GP-11-04	18.0 N	68.5 W	25-30	.009	

Table 4 compares total DNAPL concentrations of the target samples to the EOL confidence predictions for finding DNAPL in the subsurface. Concentrations for all EOL samples, except one, were very low, ranging from 0 to 0.990 ppm. In 9 different locations, the EOL survey predicted the presence of DNAPL contamination with a strong level of confidence (medium or high). However, in each case, truth sampling revealed little to no DNAPL in the groundwater. On the other hand, 14 EOL confidence predictions indicating the absence of DNAPL were established as accurate from their respective target samples. One sample taken from the UST area revealed a relatively high concentration of DNAPL at 109 ppm. Surprisingly, however, the EOL survey predicted this specific area to have little contamination.

The analysis in Table 5 shows a statistical description comparing total DNAPL concentrations in the validation samples between two EOL confidence classification groups. Table 5 presents a two-sample *t-test* of the validation data for two classes representing low (average resistivity contrast) vs. high and medium (above average to anomalous) values based on the EOL resistivity survey corresponding to depths between 12.5 and 30.5 feet below grade. The data set is problematic, since only one point is contained in the medium to high group, creating a highly unbalanced data set. This makes it difficult to accurately access the precise probability of differences between the two groups. However, assuming statistical robustness of the *t-test*, data indicate no difference between target values for the two contrasting classes, the test statistic having a probability of only *Prob* ($0.094 \leq t$). A significant difference in class would require a probability of *Prob* ($0.05 \leq t$) to correctly determine the true class 95 out of 100 times.

Table 6 presents the rank and percentile rank for target data. Data were highly skewed with the 50th percentile concentration of total measured DNAPL being just 48 ppb. This suggests the need of a log-transformation to stabilize the data distribution for statistical analysis. Geometric mean and standard deviation (mean and standard deviations of the log values) were 3.09 and .48, respectively.

Results of DNAPL concentrations in sediment samples compared with EOL confidence predictions are shown in Table 7. The location of these target samples are displayed on Figure 13. The analysis in Table 7 compares DNAPL concentrations in the sediment samples to the respective EOL prediction for the presence of DNAPL. The results show that in 8 separate locations, the EOL survey predicted a strong likelihood of there being DNAPL contamination. However, in each case, validation sampling of these target locations failed to reveal DNAPL concentrations greater than 110 ppm. In contrast, the EOL survey accurately predicted the absence of DNAPL in 6 separate locations.

The analysis in Table 8 compares DNAPL concentrations in the sediment samples to the two EOL confidence classification groups. The two groups are "High and Medium" and "Low." Results in Table 8 present a simple *t-test* analysis between the groups. The statistic indicates no difference between the two groups at the 14% probability level. General statistics of the DNAPL concentrations in the sediment samples are shown in Table 9.

There are three major geologic-section types in the Building 5 EOL survey setting:

- The artificial fill overburden that extends to 12 to 17 feet below grade,
- The Bay Mud Sediments which extend to 37 to 45 feet below grade, and
- The Merritt Sand located beneath the Bay Mud Sediments.

Table 4. Comparison of EOL Predicted DNAPL Presence to Validated Target Sample Concentrations at Alameda Point, Building 5*

Sample Location	Sample ID	Sample Depth (ft)	CVOC Concentration (ppm) in Sample	EOL Confidence Prediction for DNAPL Presence
B5A-01	B5A01-30	30	ND	Medium
B5A-02	B5A02-27.5	27.5	.006	High
B5A-03	B5A03-16	16	.110	Low
B5A-04	B5A04-17.5	17.5	.048	Low
B5A-05	B5A05-15	15	.015	Medium
B5A-06	B5A06-12.5	12.5	.149	Low
B5A-07	B5A07-12.5	12.5	.104	Low
B5A-08	B5A08-25	25	.026	Medium
B5A-09	B5A09-12.5	12.5	.266	Low
B5A-10	B5A10-12.5	12.5	.069	Low
B5A-11	B5A11-25	25	.990	Medium
B5A-12	B5A12-12.5	12.5	.169	Low
B5A-13	B5A13-12.5	12.5	.144	Low
B5A-14	B5A14-35	35	ND	Low
B5A-15	B5A15-7.5	7.5	.357	Low
B5A-16	B5A16-41.5	41.5	ND	Low
B5A-17	B5A17-41.5	41.5	ND	Low
B5A-18S#	B5A18S-30.5	30.5	ND	Medium
B5A-19S#	B5A19S-28.5	28.5	ND	Medium
B5A-20S#	B5A20S-26.5	26.5	ND	High
B1-S	B1S-7.5	7.5	30	Low
B3-S	B3S-26	26	.055	High
GP-10	GP10-7.5	7.5	109	Low

Environmental Laboratories Inc. Report March 16, 1998.
ND = Not detected.
* For samples taken by SCAPS at 7.5 to 41.5 bgs.
# Soil sample

Table 5. Statistical Description of EOL Confidence Groupings at 27 ft. and Target Analytical Data for Depths Between 12.5 ft. and 30.5 ft. Below Grade Alameda Point, CA

Analysis of Target Analytical Data for EOL Low and Medium/High Confidence Classes at ~27ft. bgs				
	Low	**Medium & High**	**Low LN+1**	**Med./High LN+1**
	ppb		ln ppb	
	15	55	2.77	4.03
	26	0	3.30	0
	990	6	6.90	1.95
	0		0	
	0		0	
	0		0	
Total	1031	61		
n	6	3		

t-Test: Two-Sample Assuming Equal Variances		
	Variable 1	***Variable 2***
Mean	2.161	1.990
Variance	7.624	4.052
Observations	6	3
Pooled Variance	6.603	
Hypothesized Mean Difference	0	
df	7	
t Stat	0.094	
P(T<=t) one-tail	0.464	
t Critical one-tail	1.895	
P(T<=t) two-tail	0.928	
t Critical two-tail	2.365	

95% Confidence Interval of the Mean Difference

Table 6. Rank and Percentile of Target Validation DNAPL Concentrations* Alameda Point, CA

ppb	ln ppb
0	0
6	1.95
110	4.71
48	3.89
15	2.77
149	5.01
104	4.65
26	3.30
266	5.59
69	4.25
990	6.90
169	5.14
144	4.98
0	0.00
357	5.88
0	0.00
0	0.00
0	0.00
0	0.00
0	0.00
30,000	10.31
55	4.03
109,000	11.60

Category	Point	Column1	Rank	Percent
4	23	11.599	1	100.00%
	21	10.309	2	95.40%
	11	6.899	3	90.90%
	15	5.881	4	86.30%
	9	5.587	5	81.80%
	12	5.136	6	77.20%
3	6	5.011	7	72.70%
	13	4.977	8	68.10%
	3	4.710	9	63.60%
	7	4.654	10	59.00%
	10	4.248	11	54.50%
	22	4.025	12	50.00%
2	4	3.892	13	45.40%
	8	3.296	14	40.90%
	5	2.773	15	36.30%
	2	1.946	16	31.80%
1	1	0	17	.00%
	14	0	17	.00%
	16	0	17	.00%
	17	0	17	.00%
	18	0	17	.00%
	19	0	17	.00%
	20	0	17	.00%

Column1	
Mean	3.693
Standard Error	0.678
Median	4.025
Mode	0.000
Standard Deviation	3.250
Sample Variance	10.561
Kurtosis	0.447
Skewness	0.703
Range	11.599
Minimum	0.000
Maximum	11.599
Sum	84.941
Count	23

Environmental Laboratories Inc. Report March 3, 1998

* Soil samples taken by SCAPS microwell technique

Table 7. Comparison of EOL Predicted DNAPL Presence to Validated Target Sample Concentrations at Alameda Point, Building 5*

Sample Location	Soil Sample ID	Sample Depth (ft)	CVOC Concentration (ppm) in Sample	EOL Prediction for DNAPL Presence
B-1	B1-17	17	ND	High
B-1	B1-17D**	17D	.182	High
B-1	B1-24	24	ND	Medium
B-1	B1-27	27	ND	Low
B-2	B2-17	17	8.270	High
B-2	B2-24	24	ND	Low
B-2	B2-27	27	ND	Medium
B-3	B3-17	17	6.240	High
B-3	B3-24	24	ND	Low
B-3	B3-27	27	ND	Low
B-4	B4-17	17	4.980	Low
B-4	B4-23	23	.006	Low
B-4	B4-27	27	ND	High
B-1	B1-17W (water)	17W	.254	High
B-2	B2-17W (water)	17W	.031	High

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* Analysis of sediment samples and groundwater taken from rotary drill borings.

** Duplicate sample

Table 8. Two Sample t-Test of Target DNAPL Concentrations in Sediment Samples Collected from 17 to 27 ft. bgs, Alameda Point, CA

Analysis of Target DNAPL Concentrations for EOL Low and High/Medium Confidence Classes at 27 ft. bgs				
	Low	High & Medium	Low LN+1	High/Med. LN+1
	ppb		ln ppb	
	0	0	0	0
	0	182	0	5.21
	0	8,270	0	9.02
	0	6,240	0	8.74
	4,980	0	8.51	0
	6		1.95	
	0		0	
	0		0	
Total	4,986	13,692		
n	8	5		

t-Test: Two-Sample Assuming Equal Variances		
	Variable 1	*Variable 2*
Mean	1.3074	4.5938
Variance	8.9414	19.8407
Observations	8	5
Pooled Variance	12.9048	
Hypothesized Mean Difference	0	
df	11	
t Stat	-1.6047	
P(T<=t) one-tail	0.0684	
t Critical one-tail	1.7959	
P(T<=t) two-tail	0.1369	
T Critical two-tail	2.2010	

95% Confidence Interval of the Mean Difference
Tetra Tech EM Inc. Report December 16, 1997

Table 9. Rank and Percentile of DNAPL Concentrations in Sediment Samples, Alameda Point, CA

ppb	ln ppb
0	0
182	5.20949
0	0
0	0
8,270	9.02051
0	0
0	0
6,240	8.7389
0	0
0	0
4,980	8.51339
6	1
0	94591
	0

Category	Point	Column1	Rank	Percent
4	5	9.0205	1	100.00%
	8	8.7389	2	91.60%
	11	8.5134	3	83.30%
	2	5.2095	4	75.00%
3	12	1.9459	5	66.60%
2	1	0	6	.00%
	3	0	6	.00%
	4	0	6	.00%
1	6	0	6	.00%
	7	0	6	.00%
	9	0	6	.00%
	10	0	6	.00%
	13	0	6	.00%

Column1	
Mean	2.571
Standard Error	1.060
Median	0
Mode	0
Standard Deviation	3.82082
Sample Variance	14.59865
Kurtosis	-0.80789
Skewness	1.05005
Range	9.02051
Minimum	0
Maximum	9.0205
Sum	33.4282
Count	13

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The porosity and matrices of the above are quite similar; i.e., all are small-grained and non-consolidated. Therefore, little if any changes in EOL resistivity will occur due to geology at this site. The fluid character was also expected to have little effect on change in resistivity at this site. The primary fluid found in the studied area was seawater.

As a result, major changes in resistivity were likely to be caused by foreign fluids and solids introduced into the subsurface by past site activities. Most relatively high resistivity zones of any consequence are likely to be associated with hydrocarbon contamination. Therefore it was assumed that all high resistivity anomalies, including those caused by free-product total petroleum hydrocarbon (TPH) contamination, would be muted in amplitude in the conductive and fluid hydro-geologic setting found in the Alameda Point area.

In the Alameda EOL survey grid, a combination of four post-survey split-spoon locations (four wells), and 21 post-survey SCAPS sample locations, all of various screening depths reaching as deep as 30 feet bgs, were tested for DNAPLs.

All these samples were found to be below the 110 ppm constituent concentration criteria used to indicate the existence of free-product DNAPLs. This indicated that quantities of free-product DNAPLs were small in the studied area. Therefore any current prediction model would fail to detect an area <10 feet across, which is the capability of the EOL. This was evident when sampling at SCAPS location 11 and the 5-foot step-out locations around it, 11-01, 11-02, 11-03, and 11-04. The water sample at location 11 showed 990 ppb DNAPL constituent concentration, ~1.0 ppm, usually a clear indication of DNAPLs in the Bay Mud Sediments. However, SCAPS samples 5 feet away, 11-01 through 11-04, did not detect any constituents >0.010 ppm.

Although significant resistivity contrasts were apparent in the 3-D survey model, the low level of actual contamination found in the soil may hinder a statistical analysis. While the correlation between contaminant level and resistivity properties will vary depending on local conditions, ground contamination of at least 110 ppm is desired to assure resistivity values much greater than those caused by naturally occurring elements.

5.2.2 Tinker AFB Building 3001 Air Logistic Center (West Side and Adjoining Land). A 3-D model and imagery was generated for the Tinker AFB site, based on the subsurface resistivity readings and distributions found within the volume surveyed. Additional maps showing resistivity contrasts at various depths are contained in GEHM (1998b) which is included in Appendix B.

The list of predicted target locations in Table 10 for Tinker AFB were developed and included within the EM resistivity site survey reports provided by GEHM Environmental (See Appendix B). Each sample reflects the confidence of DNAPL presence, at a particular location and depth, as interpreted from the EM resistivity surveys. These target sampling locations, designated by the coordinates listed in Table 10, are depicted in Figure 14. As reflected in Figure 14, the anomalous, high, and above average resistivity contrasts, indicated in red, orange and yellow, represent the zones predicted to have significant concentrations of DNAPL in the subsurface. The green and blue colored formations represent average or background resistive contrasts, and are predicted to have minimal to no DNAPL contamination.

Sampling locations (#'s 1-4) for the post EOL survey validation drilling are shown in Figure 14. Unlike at the Alameda site, air rotary drilling was used to acquire all validation samples. They are identified in this figure as "Center for Environmental Technology Sample Locations." This sampling effort was performed in April 1998 and concentrated on target locations predicted with a high level of confidence.

Table 10. GEHM's Recommended Locations to Perform Validation Sampling

Sample Location	Sample	Distance from Benchmark* X	Distance from Benchmark* Y	Ft bgs	DNAPL Presence Confidence
Recommended Sample Locations to be Validated by University of Missouri					
CET-1	1	21.6	49.0	19-21	High
CET-1	2	21.6	49.0	23-25	High
CET-2	3	20.0	40.0	19-21	High
CET-2	4	20.0	40.0	23-25	High
CET-3	5	21.6	29.0	19-21	High
CET-3	6	21.6	29.0	23-25	High
CET-3	7	21.6	29.0	25-27	High
CET-3	8	21.6	29.0	33-35	High
CET-4	9	29.0	30.8	19-21	High
CET-4	10	29.0	30.8	23-25	High
CET-4	11	29.0	30.8	25-27	High
CET-4	12	29.0	30.8	33-35	High
Recommended Sample Locations in which to Screen for Water					
CET-3	13	21.6	29.0	30-35	High
CET-4	14	29.0	30.8	30-35	High
-	15	EOL Well #2		31-41	Low

*The main benchmark is located at the northwest corner of the Ramp and Building 3001 within the test area and has arbitrary coordinates of X=0' and Y=0'. The orientation of the X value increases from east to west and the Y value increases from south to north (the locations are in feet). Water samples were taken in finished wells at 3 Sites: Well #3 and #4, and EOL Well #2.

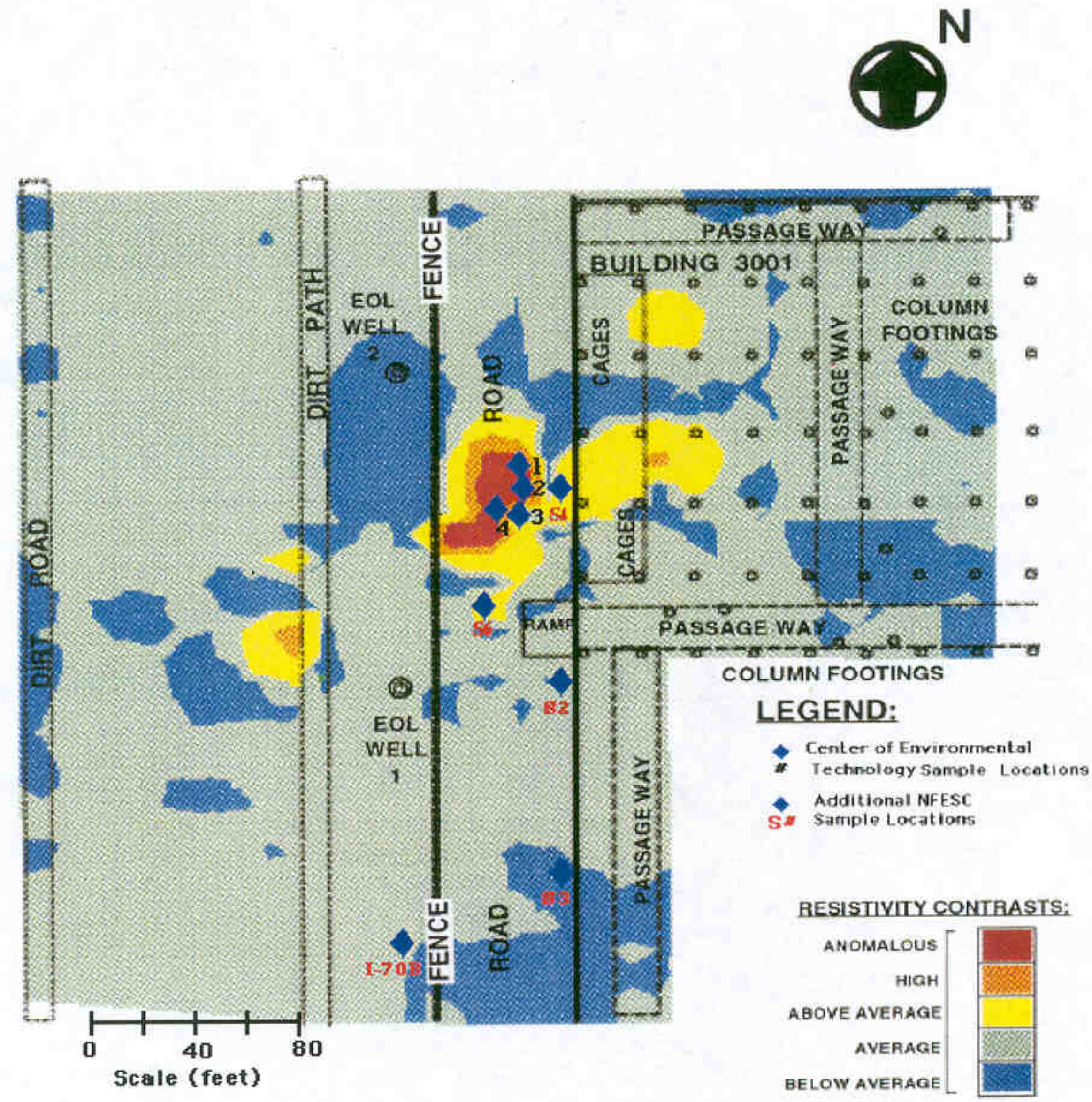

Fig. 8. Composite map of resistivity contrasts above the static water table (at 25 feet) and above the shale (at 35 feet). Center for Environmental Technology sample locations. Tinker AFB, OK.

Prepared by Center of Environmental Technology, Univ. of Missouri, Columbia
Columbia, MO

Figure 14. Composite Map of Resistivity Contrasts Above the Static Water Table (at 25 ft) and Above the Shale (at 35 feet) – CET Sample Locations, Tinker AFB, OK

Additional post survey validation samples were obtained within the survey grid in November 1998 validation drilling for a seismic demonstration. These sample locations are also shown in Figure 14, and are denoted with a red "S". These additional samples will be referred to as "NFESC" samples. The locations of the EOL receiver wells are also shown on Figure 14, identified as "EOL Well 1" and "EOL Well 2."

Table 11 lists the analytical results of all target samples collected within the Tinker AFB survey grid from project validation efforts conducted after the survey.

The comparative results between validation sample DNAPL concentrations and the EOL confidence predictions are shown in Table 12. This table compares post survey, measured DNAPL concentrations in the sediment samples to the initial probability of finding DNAPL at that particular point, as interpreted from EOL resistive anomalies. The results presented in Table 12 indicate there is poor correlation between high and anomalous EM readings and high CVOC concentrations in subsurface soils. In 14 cases, the EOL survey predicted a strong level of confidence in finding DNAPL in particular regions. However, in every case measured DNAPL concentrations were significantly less than 110 ppm. In the two cases where DNAPL concentrations did exceed the 110 ppm, the EOL prediction indicated little to no hydrocarbon contamination in that area. Overall, there was no apparent correlation between CVOC concentration and EOL predictions.

The CVOC sample concentrations shown in Tables 11 & 12 represent the total DNAPL constituent concentration for each sample. For example:

Total Measured Concentration = x DCE ppm + y TCE ppm + z TCA ppm.

However, raw data analysis of sediments showed phthalate as a major contaminant contributing to the total measured concentration for a number of samples. Phthalate was also reported in all blanks from Southwest Laboratory. Since phthalate is not a CVOC or DNAPL and had not previously been reported at the site (OGISO Environmental, 1998), it is concluded that this was a laboratory contaminant. As a result, all measured concentrations of phthalate were discounted when determining total CVOC/DNAPL concentration.

The analysis in Table 13 compares DNAPL constituent concentrations in the soil samples of two groups classified by the EOL's confidence of finding an anomaly. These confidence classes are "Low" and "Medium & High." Results in Table 13 present a simple *t-test* analysis between the groups. The statistic indicates no difference between the two groups. Table 14 presents the rank and percentile rank for SCAPS data. Again, the data is highly skewed with a mean value of 5.86 and a standard deviation of 0.68.

Very low concentrations of DCE and TCE were found in subsurface soil samples collected in the validation borings (Laboratory results from Southwest Laboratory of Oklahoma included in Appendix B). Very low concentrations of TCE were found at sample depth (20-25 feet) at validation sites #1 and #2 as well as at sample depth (35-36 feet) for validation sites #3 and #4. Very low concentrations of DCE were found in the second sample depth (23 feet) at validation site #1 and the lowest depth (36 feet) at validation site #4. These low concentrations generally agree with the modeled 3-D image (GEHM 1998b). However, concentrations of the contaminants are too low to have significantly influenced the EOL resistivity or the survey results.

Table 11. Analytical Results of Target Samples from within Tinker AFB Survey Grid

Sample Location	Sample Type	Depth (feet)	Contaminant Level (total CVOC, in ppm)
EOL Well2	water	35	3.480
CET*-1	soil	21	.269
CET-1	soil	23	.249
CET-2	soil	20	.310
CET-2	soil	25	.607
CET-3	soil	21	.297
CET-3	soil	25	.217
CET-3	soil	27	.220
CET-3	soil	35	.254
CET-3	water	35	3.500
CET-4	soil	20	.270
CET-4	soil	25	.220
CET-4	soil	26	2.200
CET-4	soil	36	.617
CET-4	water	40	7.709
NFESC S2**	water	40	.860
NFESC S3	water	40	151.000
NFESC S3	water	40	172.000
NFESC S4	water	40	1.250
NFESC S6	water	40	3.310

* Sample taken by the Center for Environmental Technology, University of Missouri.

** Sample taken by the Naval Facilities Engineering Service Center.

Table 12. Comparison of EOL Predicted DNAPL Presence to Validated Target Sample Concentrations at Tinker Air Force Base, OK

Sample Type	Sample Location	Sample ID	Sample Depth (ft)	CVOC Concentration (ppm) in Sample	EOL Confidence Prediction for DNAPL Presence
Soil	CET-2	CET2-20	20	.040	High
	CET-4	CET4-20	20	ND	High
	CET-1	CET1-21	21	.009	High
	CET-3	CET3-21	21	.004	Medium
	CET-1	CET1-23	23	.016	High
	CET-2	CET2-25	25	.007	High
	CET-3	CET3-25	25	.004	Medium
	CET-4	CET4-25	25	ND	High
	CET-4	CET4-26	26	ND	High
	CET-3	CET3-27	27	ND	Medium
	CET-3	CET3-35	35	.014	Low
	CET-4	CET4-36	36	ND	Medium
Water	EOL-Well2	EOLWELL2-35	35	3.480	Low
	CET-3	CET3-35	35	6.500	Low
	CET-4	CET4-40	40	7.400	Medium
	NFESC-S2	NFESCS2-40	40	.860	Low
	NFESC-S3	NFESCS3-40	40	151.000	Low
	NFESC-S3	NFESCS3-40	40	172.000	Low
	NFESC-S4	NFESCS4-40	40	1.250	Medium
	NFESC-S6	NFESCS6-40	40	3.310	Medium

Note: Below 110 ppm, samples are considered to have no DNAPL concentration
CET-# = U of MO Confirmation Boring taken from sample location #1,2,3, or 4

Table 13. Two Sample t-Test of Target DNAPL Concentrations in Sediment Samples Collected from 20 to 36 ft. bgs, Tinker AFB Base, OK

Analysis of Target DNAPL Concentrations for EOL Low and High/Medium Confidence Classes Between 25 ft. and 35 ft.				
	Low	High & Medium	Low LN+1	High/Med. LN+1
	ppb		ln ppb	
	297	310	5.70	5.74
	217	269	5.38	5.60
	220	249	5.40	5.52
	617	607	6.43	6.41
	254	220	5.54	5.40
		2,200		7.70
		370		5.92
Total	1,605	4,225		
n	5	7		

t-Test: Two-Sample Assuming Equal Variances		
	Variable 1	*Variable 2*
Mean	6.0401	5.6895
Variance	0.6438	0.1858
Observations	7	5
Pooled Variance	0.4606	
Hypothesized Mean Difference	0	
df	10	
t Stat	0.8823	
P(T<=t) one-tail	0.1992	
t Critical one-tail	1.8125	
P(T<=t) two-tail	0.3983	
T Critical two-tail	2.2281	

95% Confidence Interval of the Mean Difference

Table 14. Rank and Percentile of Volatile and Semivolatile DNAPL Concentrations in Sediment Samples, Tinker Air Force Base, OK

ppb	ln ppb
269	5.595
249	5.517
310	5.737
607	6.409
297	5.694
217	5.380
220	5.394
254	5.537
270	5.598
220	5.394
2,200	7.696
617	6.425

Category	Point	Column1	Rank	Percent
5	11	7.696	1	100.00%
	12	6.425	2	90.90%
	4	6.409	3	81.80%
4	3	5.737	4	72.70%
	5	5.694	5	63.60%
3	9	5.598	6	54.50%
	1	5.595	7	45.40%
2	8	5.537	8	36.30%
	2	5.517	9	27.20%
1	7	5.394	10	9.00%
	10	5.3.94	10	9.00%
	6	5.380	12	.00%

Column 1	
Mean	5.86458232
Standard Error	0.19578945
Median	5.59656667
Mode	5.39362755
Standard Deviation	0.67823454
Sample Variance	0.46000209
Kurtosis	4.62897137
Skewness	2.11072397
Range	2.31631529
Minimum	5.37989735
Maximum	7.69621264
Sum	70.3749878
Count	12

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NFESC groundwater sample S3, taken at 40 feet bgs, was highly contaminated (150-170 ppm of DNAPL). The region around S3 lies within the EOL footprint, and was measured with a below average EOL resistivity at 37 and 41 feet. EOL failed to detect this very concentrated contamination. A possible reason for this missed detection is that the water in EOL-Well 1 was contaminated, and thereby significantly reducing the measurement accuracy. Another possibility involves the fact that the resistivity of saturated rock with low porosity is much less resistive than saturated sediments. In such cases, migrating DNAPL typically produces regions of diffuse contamination that are of relatively low mass per unit of volume (mass is distributed over large volume of media).

While in contrast, LNAPL saturation tends to collect in a narrow vertical range in the capillary fringe at or just above the water table forming a layer of low electrical conductivity just above the more conductive water and saturated sediments. Therefore mass is concentrated over a small volume of media. As a result, though LNAPLs and DNAPLs are similar in resistivity, their difference in properties, such as density, can significantly impact how concentrated of a mass they form in some subsurface conditions. This can contribute to their ability or inability to be detected by an EM survey.

The EOL survey grid had more than ten well locations that were tested. This included a combination of two EOL-receiver wells, several wells and soil boring locations inside Building 3001, and 4 split-spoon target sample well locations. All samples tested from these wells were <110 ppm; the criteria used to indicate the existence of free-product DNAPLs.

At Tinker AFB there are four major geologic-section sequences in the area near Building 3001:

- The artificial fill overburden that extends to about 8 feet below grade
- The natural soils and clays which extend to about 25 feet below grade with the water table depth at 25 feet at the time of the survey
- Horizontally intermittent shales and sandstones to a depth of about 40 feet
- A continuous shale horizon which provides the shallowest perched aquifer in the section.

The resistivity in the formation fines (soils, clays, and shales) have about 1/4 the resistivity of the non-consolidated sands and 1/8 the resistivity of a gravel veneer resting on the continuous shale at depth. There should be little change in resistivity caused by the naturally occurring fluids at this site.

5.3 Technology Comparison

One main conclusion can be drawn by comparing the measured DNAPL constituent concentrations and the EOL-predicted resistive anomalies of the two sites. That is, the criteria for success outlined in *Electromagnetic Surveys for 3-D Imaging of Subsurface Contaminants* was not met.

The EOL failed to detect DNAPL at the Alameda site where post-project verification sampling, and laser induced fluorescence/videoing characterization revealed significant quantities of mixed NAPL constituents in sediment and water samples taken exactly where the investigation was focused. A U.S. Navy and University of California, Berkeley, study recovered approximately 525 gallons of mixed NAPLs in the Alameda EOL study zone after the project was completed.

Although a significant amount of subsurface contamination was observed approximately five years earlier at a location within the Tinker AFB survey, the effect of that contamination on the region's resistivity characteristics may have been insufficient today to generate a noticeably high resistivity anomaly. As discussed in Section 2.1, a minimum resistivity contrast must be present for EOL to detect

DNAPL. Attempting to correlate resistivity properties to a sediment volume that does not contain sufficient DNAPL contamination may provide insignificant results. Future field experiments should be conducted where high levels of DNAPL have been recently detected and are certain to be present.

Results from the two study sites indicate that EOL does not adequately predict where significant subsurface DNAPL is located. One possible source of error is that DNAPL contaminants were insufficiently concentrated for detection by EM resistivitiy. Another possibility is that the level of subsurface DNAPL is too diffuse to significantly alter the resistivity of the sediments. This study clearly shows that EOL technology will not successfully detect low concentrations of DNAPL in soil and sediments, and the Alameda results imply EM resistivity may not be applicable for detecting even high concentrations or even free-phase DNAPL.

As a consequence this technology demonstration has not met the required performance capabilities. Although other forms of geophysical characterization can contribute to the understanding of a site, they all lack one important feature possessed by 3-D EOL technology: the ability to use 3-D migration. 3-D migration removes distortions which so often make 2-D data (such as 2-D seismic reflection, radar, gravity, electromagnetic, or resistivity data) difficult to interpret. The effects from offline features and diffractions in 2-D work can significantly impact interpretive analysis.

Radar data could be collected using 3-D techniques, and 3-D migration could be used to clarify the image; however, radar measurements are at present limited to two dimensions, because radar still requires the use of several listening antenna with picosecond accuracy. Another problem is that the expense of each radar receiver makes development of a 100- or 200-channel recording system cost-prohibitive to develop. Finally, the depth penetration of radar is controlled by the conductivity of the surface layers and is often poor as a result.

Gravity surveys are one of the lowest cost and lowest resolution techniques. The ability to measure small distortions in the total earth gravity field is limited by the accuracy of the instrumentation, presence of noise in the data, and the model definition. Very low frequency is another very promising technique, which combines low cost with good resolution, especially on vertical fracture systems. It also is still only a 2-D technique, and contains 2-D distortions that cannot be removed.

If the EOL technique can be adapted and improved to accurately and consistently characterize and image subsurface anomalies in 3-D, it has the potential to be an economical technique that can provide much more detailed and useful imaging models than many other currently available technologies.

Section 6.0 COST ASSESSMENT

It is important to note that environmental project costing is very site specific and may vary significantly depending on a number of variables and factors. These include but are not limited to: depth of contamination; site interference due to traffic, buildings, and surface covering; the amount of drilling and sampling required to adequately evaluate if DNAPL is present; local market conditions and rates to perform drilling and sampling; availability and quality of site-specific pre-survey information; and the location, accessibility, and complexity of the site.

6.1 Cost Performance

The EOL technique has been developed for detecting LNAPLs to the point that commercial services are offered. Hence, there are no further startup costs associated with setting up this technology. In addition, demobilization costs are relatively insignificant for easily accessible sites. The majority of the costs associated with this technology involve operation and maintenance (O&M) of the system.

This technology measures cost performance per unit of surveyed area. Costs can reach upward to several thousand dollars per day depending on the number of variables associated with the particular project site. These variables can include: complexity of the site (i.e., number of buildings and other obstructions on the site); number and depth of the wells; pre-screening information that is available; local market conditions and rates; and the location and accessibility of the site.

Since the same EOL technique used to detect LNAPLs is used to detect DNAPLs in the subsurface, cost performance data can be appropriately drawn from the more commercialized and frequently applied LNAPL studies. However, since the results of this technology demonstration were inconclusive with respect to the direct detection of DNAPL, a detailed and accurate cost comparison and/or relation between the two applications is difficult to present.

6.2 Cost Comparisons to Conventional and Other Technologies

Shown below are the costs associated with performing a typical 3-D resistivity survey encompassing approximately a 2-acre grid. (This information has been provided by GEHM Environmental.)

Site Review	$ 1,000
EM Resistivity Well Installation	$ 8,000
Data Acquisition	$18,000
Data Processing	$10,000
Survey QA/QC Verification Boring	$ 6,000
Data Display and Reporting	$ 1,500
TOTAL	**$44,500**

Note: Mob/DeMob costs will depend on the location of the site.

Table 15 presents a breakdown of the cost of key activities related to the surveys and validation performed at Alameda Point and Tinker AFB.

Table 15. Project Cost Breakdown per Site[a]

Activity	Alameda Point ($)	Tinker AFB ($)
Drill Wells for EOL Survey	12,484	26,840
Samples for EOL Survey	800	800
Conduct EOL Survey	39,804	18,293
Generate EOL Survey Report	8,327	8,526
Conduct verification drilling and sampling	64,403	51,412
Mob/De-Mob	8,000	8,000
Generate Project Summary Report	20,391	20,391
Approximate survey cost per acre	154,209	134,262

(a) Surveyed area is 1 acre.

The following details related to costs and activities for the work performed at the demonstration sites may be useful for planning future EM resistivity surveys:

- Advantageous cost benefits are most frequently found in the reduction of wells required to perform a given site characterization.
- EM resistivity surveying becomes much more cost-effective at sites that require extensive well drilling and sampling.
- EM resistivity eliminates costs associated with site disruption and disturbance that would be unavoidable with conventional drilling and sampling techniques.
- Drilling and sampling costs were strongly influenced by each site's geologic setting. For example, sites with subsurface geologic conditions favorable to direct push methods are less expensive than those that require conventional drilling methods.
- The cost of demobilization was relatively insignificant. It consisted of the minimal effort for personnel to pack up the 3-D EM resistivity instrumentation and leave the site.
- Given that 3-D EM resistivity surveys are services provided by commercial agencies, any costs for maintenance and replacement of system components are included in individual project costs.

Aside from site characterization savings, the greatest contributor to the overall savings is having a technology that provides more detailed information in less time.

Table 16 below, provided by GEHM Environmental, shows the breakeven point between an EM resistivity survey with drilling and a traditional drilling approach for the characterization of an LNAPL site at Naval Air Station North Island. This project cost breakdown clearly depicts the point at which traditional drilling becomes more cost effective than the EOL technology when surveying a 2-acre site. In this example, it would be necessary to determine if 15 traditionally-drilled wells adequately characterize the extent of contamination over the 2-acre site. If a preliminary study of the site's history reveals that more than 15 characterization wells may be required to accurately delineate a plume, the EM survey technique should seriously be considered.

In addition, it is important to note that this cost comparison did not take into account additional time and costs that would be incurred to apply conventional site characterization methods. The EM survey

Table 16. Cost Breakeven Point between Traditional Drilling and EOL with Drilling for a 2-Acre Site

Comparison Category	Traditional Approach	EOL with Drilling Approach
1. Background information known prior to comparison	2 acres with known hydrocarbon contamination; 2 acres unknown	2 acres with known hydrocarbon contamination; 2 acres unknown
2. Typical monitoring well construction	40-foot, 2-inch diameter PVC/Schedule 40	40-foot, 2-inch diameter PVC/Schedule 40
3. Monitoring wells needed outside buildings	13 wells (distributed over 2 acres) = $13,000	8 wells (3 EOL receiver wells; 3 wells for data correlation model validation; and 2 wells for contingency) = $8,000
4. Monitoring wells needed inside buildings	2 wells = $3,000	0 wells
5. Mobilization/Demobilization (drill rig)	= $4,000 ($2,000/rig) 1 rig outside, 1 low-profile rig for in building	= $2,000 1 rig for outside
6. Drilling costs (includes rig, drill crew, materials, and incidentals)	$1,000/well (outside) $1,500/well (inside)	$1,000/well (outside)
7. Well logging, development, and investigative derived waste disposal	$370/well (2 hours labor at $60/hr + $50/drum + $200/drum disposal cost) = $5,550	$370/well (2 hours labor at $60/hr + $50/drum + $200/drum disposal cost) = $2,960
8. Sampling and analytical costs (4 samples collected per well; 4 TPH-diesel and 1 SVOC analysis)	$600/well = $9,000	$600/well = $4,800
9. EOL costs (2 days field work, mobilization/ demobilization, prepare report)	= $0	= $17,800 ($7,000/day for 2 days + $3,800 mob/demob)
Total Estimated Costs	**$ 34,550**	**$ 35,560**

Notes: TPH = Total Petroleum Hydrocarbons
SVOC = Semivolatile Organic Compounds

technique's cost-effectiveness becomes clearly apparent at sites that require extensive well drilling and sampling. For example, the 2 acres at NAS North Island adjacent to the LNAPL EM survey area required 62 wells and six months to completely characterize using conventional drill and sample methods. A final hidden cost savings of using EM resistivity, not depicted in Table 16, is the fact that EM surveys are minimally disruptive to normal site operations. In this case, EM did not disrupt ongoing engine overhauls at the Naval Air Depot (NADEP) or block the adjacent street that carried critical NADEP traffic.

Section 7.0 REGULATORY ISSUES

Many sites at DoD installations are listed under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). These DoD installations are engaged in active Installation Restoration Programs. Remedial Investigations are an integral element of the CERCLA process. A main objective of a Remedial Investigation is to determine the nature and extent of contamination at waste sites so that an effective remedial design can be implemented. 3-D EM resistivity imaging tends to support these efforts by providing information on subsurface site geologic features and contaminant distribution.

Electromagnetic resistivity surveys are relatively non-invasive; however, they do require that at least two instrumentation wells are located and, if necessary, installed within a few hundred feet of the region of interest. In addition, subsurface samples must be taken, using either conventional drilling and sampling techniques or direct push methods. As a result, the prevention of cross contamination through an upper confining layer situated above an uncontaminated aquifer is a primary concern at any site. Steps were taken to mitigate this regulatory concern. The Geoprobe® and Site Characterization and Analysis Penetrometer System (SCAPS) methods consisted of pushing a small diameter probe into the ground, and were a relatively slight intrusion into the subsurface. Both wells were destroyed after the EM survey, and within two weeks after the well installation. These push borings were limited to the upper confining layer, and were immediately grouted upon recovery of samples. These procedures minimized any potential for creating preferential pathways through which DNAPLs could migrate.

In addition, contractors obtained proper clearances and permits for the installation of the borings, and had each potential push location cleared for utilities. The contractors also disposed of investigation-derived wastes (IDW) that were generated during this effort in accordance with Resource Conservation and Recovery Act (RCRA) guidelines. IDW consisted of the wash-down water used to decontaminate the Geoprobe and SCAPS probes and samplers after each use, as well as all borehole and well drill cuttings. These wastes were contained in 55-gallon drums per regulatory requirements. An additional permit was required to temporarily accumulate the IDW at the site.

A final regulatory issue involved the transmission of electromagnetic radiation from the equipment. The magnitude of the electromagnetic field generated by the signal transmitter was less than an EM field generated by the 15-amp (A) power lines in a 10-x-10-foot room, when standing 4 feet from the transmitter. Thus, the magnitude of EM radiation at the site was relatively small. Regulatory and safety issues were avoided by maintaining a 4-foot safety distance from the energized transmitter.

Section 8.0 TECHNOLOGY IMPLEMENTATION

8.1 DoD Need

It is estimated that the Navy alone is responsible for remediating in excess of 1,000 chlorinated-solvent or dissolved-DNAPL contaminated sites. DNAPL contamination is often very expensive and difficult to identify, characterize, and remediate because it readily migrates through small-scale fractures and heterogeneities in the soil, undergoes limited degradation in the subsurface, and traditional sampling methods increase the risk of cross contamination.

8.2 Implementation and Transition

NFESC will be responsible for evaluating the capabilities and limitations of using 3-D EM resistivity surveys to locate DNAPLs. A fact sheet will be developed that describes the appropriate uses and expected benefits of EOL technology, particularly with respect to DoD needs. This most recent demonstration of EOL technology has shown that it is not ready for transfer and implementation at DoD sites. However, once the technology has proven to be accurate and consistent, NFESC will play a critical role in transferring the success of the system throughout the DoD.

Section 9.0 LESSONS LEARNED

The results from the two sites that hosted demonstrations are at best inconclusive because EOL imaging provided inaccurate and inconsistent predictions or indications of DNAPL presence in areas proven to have significant NAPL and DNAPL contamination. An additional limiting factor is that since the data is remote and is modeled, the location is of suspected anomalies are not exact. Demonstrating the EM surveys with these variables in mind will significantly reduce the margin of uncertainty and error associated with the system and the user. When EM site characterization for DNAPL in the field becomes better understood under controlled variables, its ability to readily detect and image subsurface anomalies under varying conditions can be enhanced.

The knowledge gained and lessons learned from this field application will be applied in future studies and should improve the assessment of this innovative site characterization technology.

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APPENDIX A
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APPENDIX B – Data Archiving and Demonstration Plan

The Naval Facilities Engineering Service Center will maintain copies of all pertinent documentation that was developed during the course of this demonstration effort. This includes such items as the Technology Demonstration Plan, individual EOL site survey reports, drilling and sampling records, laboratory results, etc.

To obtain any information regarding this project, contact:

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